Dear Dr. Valerio Lucarini and dear reviewers,

Please find below:

1. all the reviewers' comments with our responses as published at the ESD website but with additional comments (highlighted) explaining how we proceeded to arrive at the revised manuscript.
2. The revised manuscript with all the changes highlighted.

The changes corresponding to each reviewer comments and additional text modifications by the authors are marked in different colours.

Referee 1 - Pink
Referee 2 - Green
Referee 3 - Blue
Authors' additions and further comments - Purple

We have uploaded the revised manuscript with all the corrections suggested by the reviewers. We thank the reviewers for helping us improve the manuscript substantially through their valuable comments and suggestions.

With best regards,
Sirisha Kalidindi

Response to Referee #1 comments:

Overview: The authors run a sophisticated global climate model (GCM) with a surface that is covered by a sophisticated land model. They assume a globally uniform ground water table, representing efficient surface water transport. Interestingly, they find bistability between two climate states, a hot and dry (HD) state and a cold and wet (CW) state. I have never seen anything like this before and it is definitely worth publishing. I think the authors should do a bit more work to understand why the model produces this behavior, then the paper will be ready to be published. I have some comments that hopefully will help with this.

We thank our first referee Dr. Dorian Abbot for the very immediate yet a detailed review of our manuscript. Please find below our responses to his comments.

Comments:
Referee #1 comment - Mechanism: In the final paragraph of the introduction the authors restrict the scope of the paper so that it doesn't include investigating the mechanism of bi-stability. I think at least some investigation of the mechanism is necessary so that this paper stands as an independent work that doesn't rely on future work and to convince the reader that the observed behavior isn't simply due to some bug in the land surface scheme.

Authors' response: *We do understand that including the mechanisms of bi-stability in the same paper would give a more complete picture to the reader. However, the mechanism of the bi-stability is very complex and including all the details would drastically increase the length of the paper. A complete paper on the mechanisms of bi-stability is already in preparation. If the Editor feels it is necessary, we could think about submitting our forthcoming paper on the mechanisms of bi-stability as a part two of the present paper to ESD as well so that together part one and part two papers could stand as an independent work.*
We provided additional discussion on feedbacks responsible for stabilization of the two terra-planet states (Sect. 3.3 and 3.4) in our revised manuscript.

Referee #1 comment: The way I would approach this is to first run the model in "swamp" configuration: with a global mixed layer ocean of 1 m depth and zero ocean heat transport. Presumably you will reproduce a roughly Earth-like climate. Then I would turn on the land surface model, but choose schemes and parameters to match the swamp configuration as closely as possible. Then slowly turn more schemes on or change parameters until you get bistability. This should allow you to identify the specific physical parameterization that allows for bistability. It must be related to evapotranspiration, since that's the key difference between a swamp surface and a real land surface.

Authors' response: *We thank Referee #1 for suggesting an approach to better understand the mechanism behind the bi-stability. Incidentally, we already performed simulations of the type proposed by the Referee #1 and this was indeed how we found the bi-stability that we describe in our paper. Our model in the "Swamp configuration" is able to successfully reproduce the climate of an "Aqua-planet" configuration. Starting from this setup, we sequentially changed different parameters and schemes in our land surface model (Table 1) and we clearly saw that when the ground water table was lowered, the bi-stability emerged. In Table 1 we list our sequence of simulations and in Fig. 1 we show the resulting zonal structure for temperature and precipitation. With this additional information, we hope it is convincing enough for the reader to believe that the bi-stability is not due to some bug in the model's land surface scheme. We will include this information in the Appendix of the manuscript to demonstrate that indeed the restricted atmospheric access to water causes the appearance of the bi-stability.*
We included all the information regarding the approach followed to arrive at the bi-stability in Appendix A of the revised manuscript.

Referee #1 comment – Surface energy balance: Surface energy balance is important for global-mean evaporation, and therefore precipitation. All else equal, more absorbed shortwave at the surface should mean more evaporation and more precipitation. That's why it seems odd that the planetary albedo should be lower in the HD state, but the global-mean precipitation should also be so much lower.

Authors' response: *Referee #1's statement "more absorbed shortwave at the surface should mean more evaporation and more precipitation" – is only valid for an Earth-like planet with large oceans. However, in our HD state, even though the tropics receive huge amounts of net radiation at the surface, the uppermost soil layers in the tropics dry out quickly. Dry uppermost soil layers imply small evapotranspiration leading to no precipitation which in turn leads to even less evapotranspiration. This self stabilizing mechanism maintains the HD state.*
More detailed explanations about the mechanisms stabilizing the CW and the HD state are presented in Sect. 3.3 and 3.4 of the revised manuscript.

Referee#1 comment: One possibility is that much more of the surface heat is lost through sensible rather than latent heat in the HD state. Another is that the planetary shortwave absorption is not a good proxy for surface shortwave absorption because of differential atmospheric absorption of radiation in the two cases. I think it's worth calculating the terms in the surface energy balance (both zonal mean and global mean) and using this to explain why the HD state seems to be able to absorb so much more shortwave yet have such a low evaporation. If you can explain this, it might also help your investigation into the mechanism for bistability.

Authors' response: *We agree with the Referee #1 about his first suggestion that much more of the surface heat is lost through sensible rather than through latent heat in the HD state (see Fig. 2 below). Additionally, most of the heat is lost from the surface by terrestrial radiation in HD state. Upon re-submission we would include a brief discussion about the surface energy balance in section 3 of our revised manuscript and add a figure in the appendix (Fig. 2 here).*
We did not include any additional figures for surface energy balance as energy transport curves in Fig. 5 already convey the information discussed above.

Referee #1 comment: Also, I wonder if this could be connected to why bistability is lost for Earth-like obliquity. It would be really great if you could explain why increasing obliquity disrupts the bistability, and maybe analyzing the surface energy balance would help.

Authors' response: *We have so far not analyzed the reason why bi-stability is lost for Earth-like obliquity in detail and it is one of our plans for the future. But we speculate that for Earth-like obliquity, the bi-stability is lost due to the seasonal migration of the rain bands towards the lower latitudes. The seasonal migration of rain bands facilitates seasonal rain in the dry tropics. Since soil moisture has a memory lasting for several weeks to months this causes the soils in the tropics to remain wet even during the dry season. Thus there is always soil moisture in the originally dry tropics to allow for continuous evapotranspiration and precipitation. And this destroys the HD state so that the planet is always self stabilized in the CW state. We will include this speculation in the section about seasonality in our revised manuscript.*
We included this speculation in the section 7 about seasonality in our revised manuscript.

Referee #1 comment – Vertical Temperature Structure: One thing I was wondering about is the vertical temperature structure in the two states, since convection is probably important for the bistability. I think it would be worth plotting and thinking about this.

Authors' response: *We have attached the figure for vertical temperature profile including potential temperature in the tropics for the two terra-planet states (see Fig. 3 below). But vertical temperature structure does not explain much about the bi-stability, the restricted atmospheric access to water causes the appearance of the bi-stability*

Referee #1 comment – A related point is that near the outer edge of the habitable zone we expect very high CO2 levels, probably at least 1 bar. A large radiative cooling in the atmosphere could strongly affect the vertical temperature structure. It would be interesting to do some test runs at very high CO2 and see if the HD state can persist under these conditions, since the authors connect the HD state with the outer edge of the habitable zone.

Authors' response: *We thank the Referee #1 for his interesting suggestion. Unfortunately, we cannot run such simulations as our model parameterizations are not suited for very high CO_2 concentrations and hence it is beyond the scope of the present paper.*

Simulations	Background soil albedo	Surface roughness	Heat capacity	Snow albedo	Water reservoir depth
Aqua-planet	0.07	Ocean	Ocean	0.07	50 m slab ocean, no heat transport
Swamp1	0.07	Ocean	Ocean	0.07	Constant ground water table at a depth of 0.3 m
Swamp2	0.07	Land	Land	0.07	Constant ground water table at a depth of 0.3 m
HD	0.07-0.14	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m
CW	0.15-0.24	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m

Table 1. Summary of simulations performed to illustrate the procedure followed by which we found bi-stability on our terra-planet.

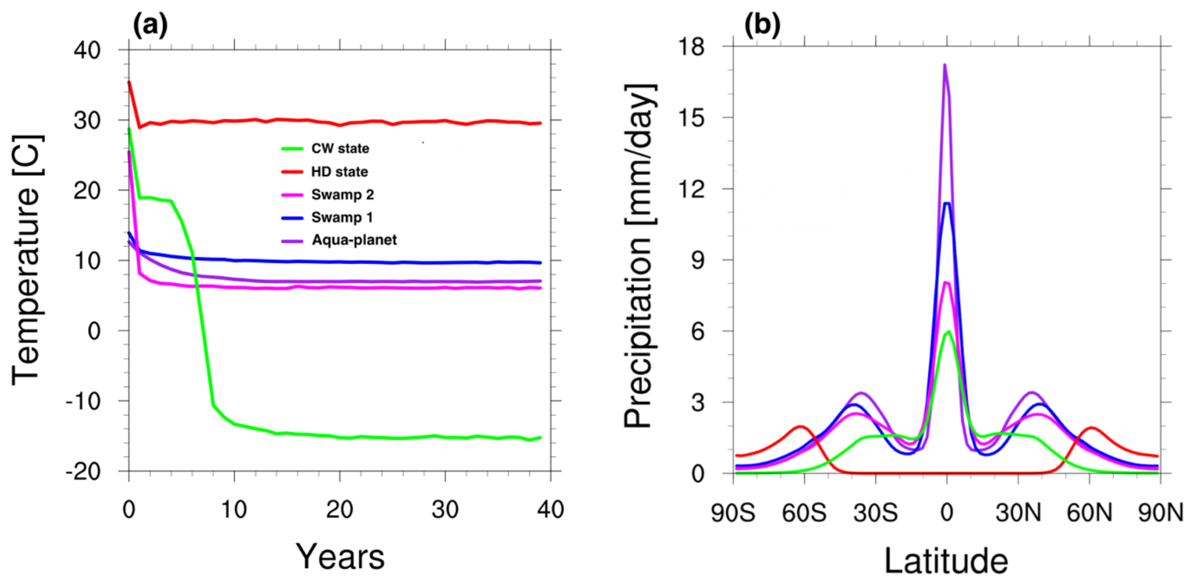

Figure 1: (a) Time series of global mean surface temperature (°C) and (b) annual mean meridional profile of precipitation (mm day^{-1}) for different simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

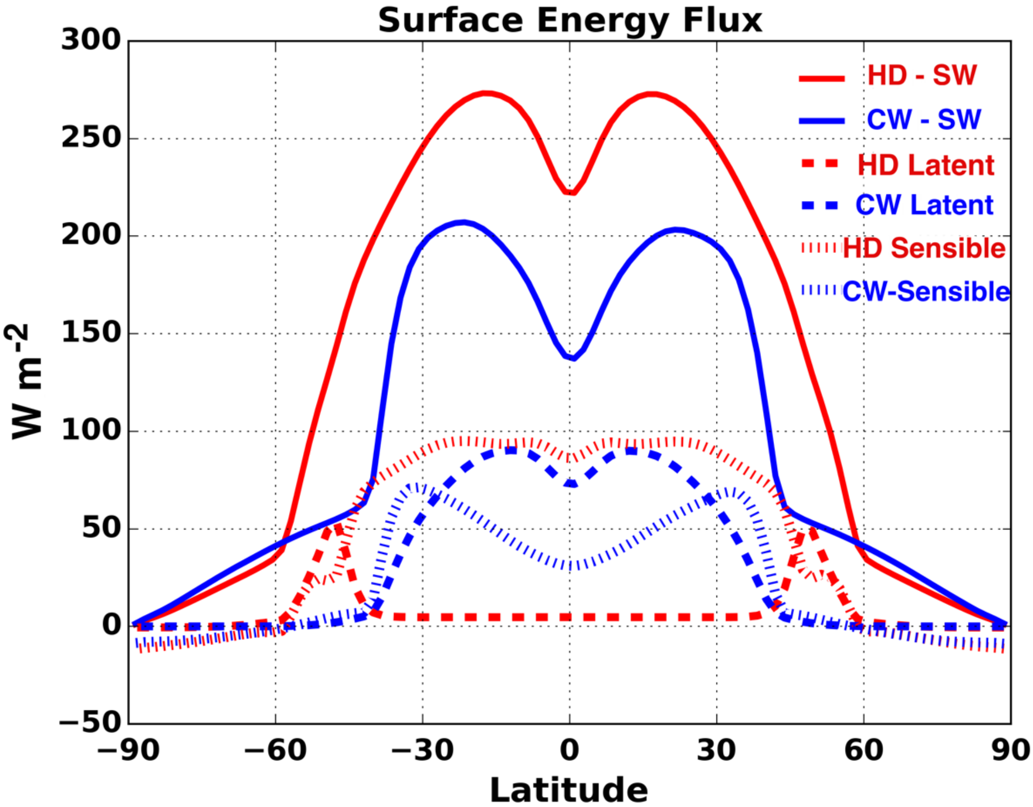

Figure 2: Annual mean meridional profiles of Net shortwave radiation at surface (SW), latent heat flux (Latent) and sensible heat flux (Sensible) for the two terra-planet states: HD (α = 0.14) and CW (α = 0.15) in the simulations Z14 and Z15 averaged over a period of ten years.

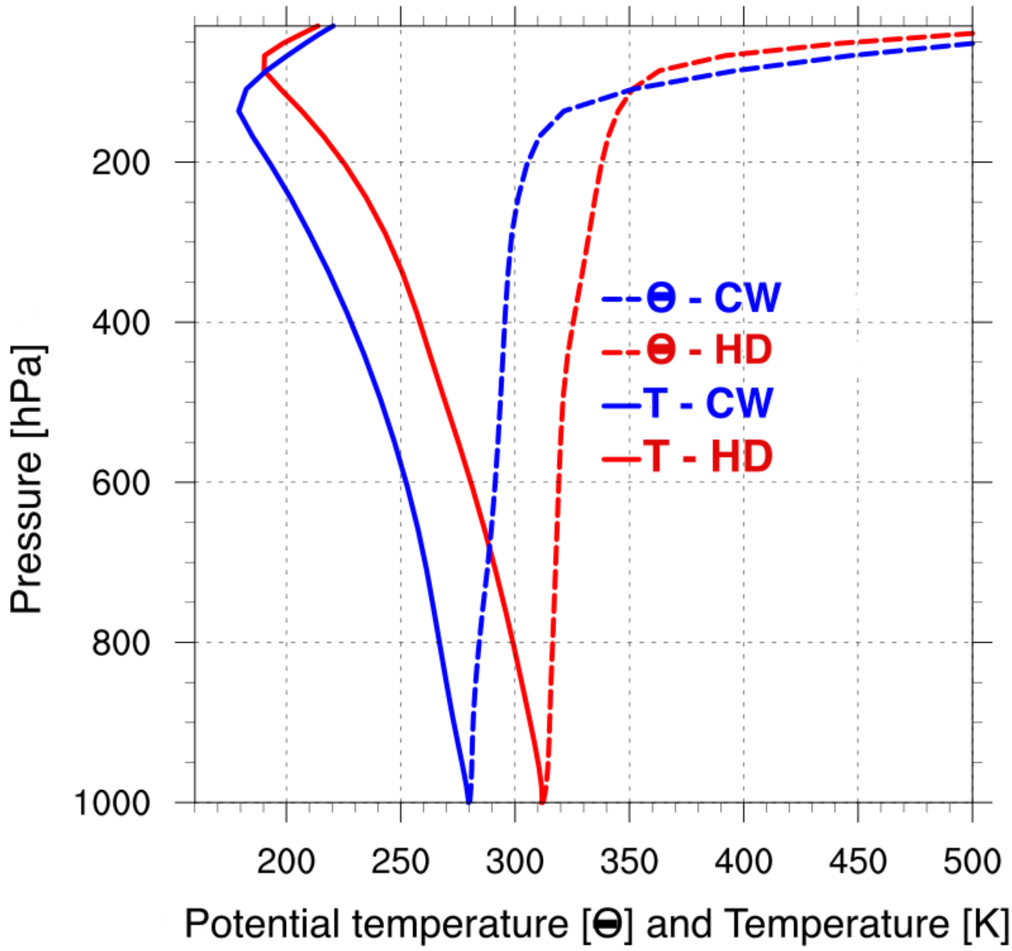

Figure 3: Vertical profiles of Temperature and potential temperature in the tropics for the two terra-planet states in the simulations Z14 (HD state) and Z15 (CW state) averaged over a period of ten years.

Response to Referee #2 comments:

General comments

Referee #2 comment: In this paper, the authors modelled the climate of a terra planet (or land planet), a planet with a global land surface, without ocean. The particularity of the present study is the presence of an unlimited underground water layer providing water at all latitude but behaving differently as an ocean. The authors perform various simulations, changing obliquity, snow albedo and a test with a different convection scheme.

Depending on the value of the surface albedo, two different stable climate states appear. A hot and dry state and a cold and wet state. This latter is a novelty, due to the addition of the underground water reservoir and is an interesting result. However, as the main novelty is the presence of an underground reservoir, more discussion would be useful. For instance the authors tested only a fixed depth of 1.2m to mimic a "recycling" of water from higher to lower latitudes. This setup is somewhat artificial and a justification of the current assumptions as well as the potential effect of varying them would be welcomed.

Authors' response: *We thank the referee #2 for the comment. Our main idea behind this study was to explore how water recycling can shape the climate of water-limited planets. In the traditional land planet studies with limited water inventories, all the water on the planet is exported to the higher latitudes by atmospheric circulation where it is permanently piled up as snow on the icecaps and is no longer a part of the hydrological cycle and has no effect on the climate. However, in reality there is a limit on how large an ice cap can grow and beyond a particular threshold, parts of the ice cap can break off and flow towards warmer regions due to gravity and lead to liquid water formation. Also, as the thickness of the ice cap increases, geothermal flux at the bottom of the ice caps can cause melting and liquid water formation. This water then flows back to the lower latitudes through river flows or if the surface is porous like our present-day Earth the water can percolate into the ground and refill some kind of underground reservoir. Thus, it again becomes a part of the hydrological cycle and therefore can affect the climate in the lower latitudes. In our study, we mimic such a water recycling from higher to lower latitudes by means of a homogenous global subsurface reservoir. Indeed, referee #2 is correct concerning our assumption of a homogenous recycling over the whole globe to be artificial. In reality, recycling may occur at different speeds and might be less or more effective than what we consider in our study. Based on the speed of recycling, the water level of this subsurface reservoir would vary. In our study, the choice of the fixed ground water table depth of 1.2 m was not random and we performed a sequence of simulations starting from a swamp simulation and changed different parameters (including the depth of the ground water table) and various schemes in our land surface model (Table 1; Fig. 1) until we arrived at the bi-stability for a ground water table depth of 1.2 m. Overall, our study should be considered as a first attempt towards understanding how water recycling can shape the climate of land planets with reasonable assumptions. We will include all the information regarding the sequence of simulations performed to arrive at the bi-stability in the appendix of the revised manuscript. We have included information regarding how we arrived at the particular depth of the subsurface reservoir in appendix A of the revised manuscript and added additional explanations for the interpretation of the subsurface reservoir to the section 2.2.*

Specific comments

Referee #2 comment: lines 29-30 of page 4. The authors describe the Hadley cells in Figure 4 "narrower" and "wider". Is it in the vertical direction? Because they look in both cases 30 degrees wide.

Authors' response: *The reviewer is indeed correct that the Hadley cells in both the terra-planet states look very similar and have the same width close to the surface. But with height the Hadley cell in the CW state gets slightly narrower compared to that in the HD state (when measured around 500hPa). We will rewrite the sentences related to width of the Hadley cell in the revised manuscript to make our point clear.*

The text related to width of the Hadley cell is modified accordingly in section 3.5 of the revised manuscript.

Simulations	Background soil albedo	Surface roughness	Heat capacity	Snow albedo	Water reservoir depth from the surface
Aqua-planet	0.07	Ocean	Ocean	0.07	50 m slab ocean, no heat transport
Swamp1	0.07	Ocean	Ocean	0.07	Constant ground water table at a depth of 0.3 m
Swamp2	0.07	Land	Land	0.07	Constant ground water table at a depth of 0.3 m
HD	0.07-0.14	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m
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Table 1. Summary of simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

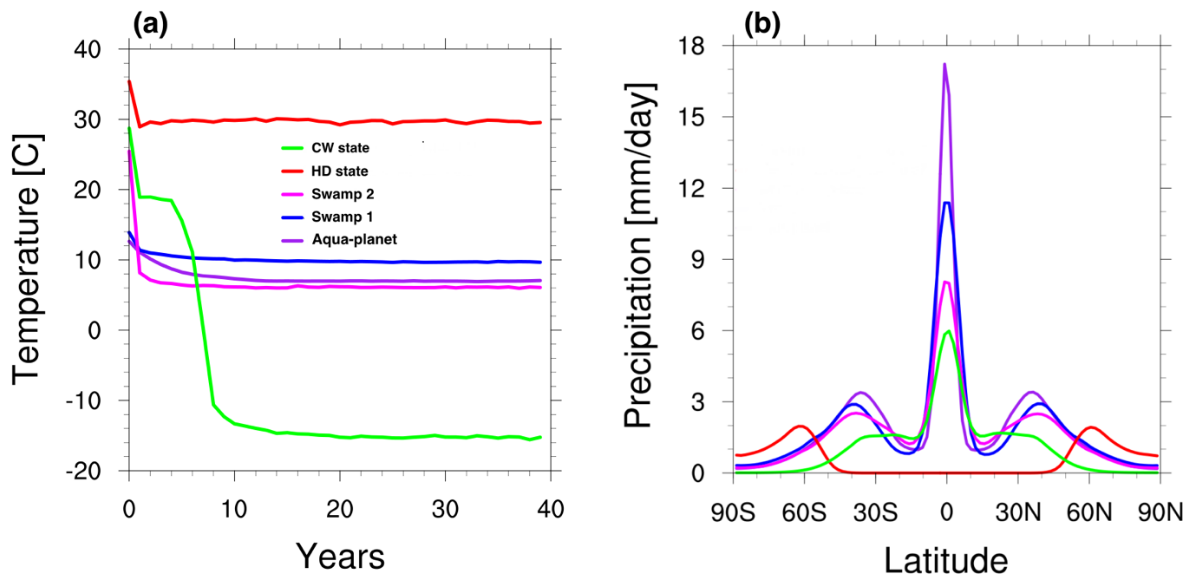

Figure 1: (a) Time series of global mean surface temperature (°C) and (b) annual mean meridional profile of precipitation (mm day^{-1}) for different simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

Response to Referee #3 comments:

Summary:
This paper explores a climate bifurcation for dry/desert planets, including implicit water cycling through the assumption of a sub-surface aquifer. This work represents a step forward from the classic work by Abe et al. 2011. I feel that this paper is interesting and deserves to be published. I suggest that the authors try to do more to explain why this transition happens, in terms of the cloud albedo and water vapor greenhouse forcing.

We thank our referee for very interesting comments and suggestions on our manuscript. Please find below our responses to the referee#3 comments.

General comments:
Referee #3 comment: "It should be noted that the present paper is mainly descriptive in nature and is not meant to explain the mechanisms for the emergence of the two climate states and the way the transition between them happens. This is still under investigation." You should explain the mechanisms for the emergence of the two climate states in this paper. This should be included in this paper to make it complete. I think you can do so by examining the changes in cloud albedo and water vapor greenhouse effect.

Authors' response: *We thank the Referee#3 for suggesting us to look at the role of clouds and water vapor greenhouse forcing to explain the emergence of two drastically different states. Indeed, it is true that the two terra-planet climate states display considerably different patterns of cloud cover and water vapor in the lower latitudes (Fig. 1). In the HD state, the cloud cover in the low latitudes is exclusively composed of high level clouds with very low liquid water content (Fig. 2). The reason being, the high surface temperatures in the lower latitudes in the HD state raise the water vapor saturation limit of the atmosphere and the height at which condensation and cloud formation occurs. High clouds are more transparent to shortwave radiation, at the same time they reduce outgoing longwave radiation and thereby keep the planet hot and stabilize the HD state. With an increase in background soil albedo beyond the bifurcation threshold, the water vapor saturation limit of the atmosphere and the height at which the clouds can form is lowered due to the lowering of surface temperature, thus leading to an increase in low level cloud cover. Increase in low level cloud cover increases the planetary albedo and keeps the planet cool and self stabilized in the CW state. Overall, the self stabilizing cloud albedo feedback does play a role in the transition from the HD to the CW state (we briefly mentioned this in Sections 6 and 8 in the original manuscript). However, a complex sequence of steps is involved in the formation of low level clouds before the self stabilization of the planet in the CW state by the cloud albedo feedback. Including all these complex mechanisms would drastically increase the length of the paper and hence we prefer to present the explanations regarding the mechanisms involved in the transition in a separate paper (already in preparation). If the Editor feels it is necessary, we could think about submitting our forthcoming paper on the mechanisms of bi-stability as a part two of the present paper to ESD as well so that together part one and part two papers could stand as an independent work.*
We provided additional discussion on the role of cloud and hydrological feedbacks in stabilizing the climate of the two terra-planet states in Sect. 3.3 and 3.4 of our revised manuscript.

Referee #3 comment: In your simulations, water is in theory made available everywhere on the planet via diffusion of water from the subsurface water-table into the atmosphere. How is the temperature, clouds, and water vapor in your terraplanet simulations different from an aquaplanet case, given an equal albedo? It would be useful to run 1 aquaplanet simulation with albedo = 0.07 for comparative purposes. (Note that 0.07 is fine for a typical ocean albedo).

Authors' response: *This is part of what we already did: We performed a series of simulations starting from an aqua-planet setup to arrive at the bi-stability (please see Fig. 3 and Table 1 below). In Fig. 4 below you find the requested plots for annual mean meridional profiles of (a) surface temperature, (b)* *vertically integrated water vapor, (c) vertically integrated cloud cover for an aqua-planet simulation with albedo = 0.07 and terra-planet simulations with the same background soil albedo value (0.07) but initialized differently: from a warmer state (HD – 0.07 simulation) and from a colder state (CW - 0.07 simulation).*

The aqua-planet climate resembles more closely to the CW - 0.07 simulation and is about 22K colder than the HD-0.07 simulation. However, the atmosphere in the terra-planet simulation (HD – 0.07) can hold a similar amount of water vapor as in the aqua-planet simulation due to higher temperatures in HD-0.07 (Fig. 4b). The cloud cover at the lower latitudes in terra-planet simulation (HD – 0.07) is lower compared to that of the aqua-planet simulation (Fig. 4c) and is mainly comprised of high level clouds whereas in the aqua-planet case (also for CW-0.07 simulation), it is dominated by low level clouds.

Specific comments:

Referee #3 comment: I may suggest changing the title from ". . .Earth-like terra planet" to ". . .Earth-like Dune planet", or ". . .water-limited terrestrial planets." The term "terra-planet" isn't a common term in the literature. Also, the adjective "Earth-like" connotes a planet where surface liquid water is freely available. These dry worlds are perhaps more so Mars-like in description. OR, due to the ambiguity of the term "terra-planet", you should explicitly state somewhere early in the Abstract, perhaps the in the first sentence, that you are dealing with water-limited land planets.

Authors' response: *Our main idea behind naming the planet as terra is to contrast it from the well known aqua-planet. The word "terra" means "land" in Latin. To avoid ambiguity regarding the term "Earth-like", we shall in our revised manuscript explicitly define "Earth-like terra-planet" as a water limited terrestrial planet in the first sentence of the abstract.*
Done.

Referee #3 comment: Page 2, line 5 "Second, terra-planets with optically thin atmospheres (like present day Earth's atmosphere) can maintain their inner edge of the habitable zone much closer to their parent star compared to aqua-planets due to their higher surface albedo (Abe et al., 2011; Zsom et al., 2013)." While it is true that dry planets will have a higher albedo than ocean planets, this is just one piece of the puzzle, and I don't think the dominant one. One of the primary reasons that dry planets can maintain habitability at higher stellar fluxes is due to the lack of available water vapor. With less water in the system, the water-vapor greenhouse feedback is severely muted and thus there is significantly less greenhouse warming of the climate system. This is true regardless of surface albedo.

Authors' response: *We thank the referee#3 for pointing out the primary reason why dry planets can maintain habitability even at higher stellar fluxes. We will modify the text as suggested by the referee#3 in our revised manuscript.*
Done.

Referee #3 comment: Page 3, line 5. Can you give the model horizontal resolution in either degrees lon X degrees lat, or in number lon grids X number of lat grids?

Authors' response: *The model has a horizontal resolution of R2B04 equivalent to a resolution of an evenly distributed rectangular grid of about ~ 160 Km. We would modify the text in the revised manuscript to make it more clear for the reader.*
Done.

Referee #3 comment: what does "Leaf Area Index (LAI) =3" mean? Is your surface vegetated or bare soil? How might the vegetation type affect your results?

Authors' response: *Yes, there is something that one could call vegetation, because our model includes besides bare soil evaporation also a transpiration pathway for soil water to reach the atmosphere. The value of LAI controls how much surface in a grid cell participates in transpiration, while the rest*

exhibits bare soil evaporation. But we consider the value of the LAI here only as a means to parameterize the atmospheric access to water, like other hydrological parameters of the model, e.g. soil porosity, hydraulic conductivity, or depth of the 'subsurface reservoir'. Therefore, and because other aspects of vegetation like plant growth or phenology are missing, we do not use the word 'vegetation' in our paper. We would rewrite the the text regarding the LAI in the revised manuscript to make it more clear for the reader.
Done.

Referee #3 comment: "overland water recycling" You are not really considering overland water recycling. You are considering a ubiquitous sub-surface aquifer that sources water into the model. Thus you are considering "subsurface" water recycling.

Authors' response: *We agree with the Referee#3's comment regarding the term "overland water recycling". However, it also not just "subsurface" water recycling but imagine it as a combination of recycling happening via ice/river flows over the land and, subsurface flows. We will try to find a more concise and appropriate term which represents both these flows for our revised manuscript.*
After considering several alternatives, we decided to stick to the term "overland", particularly because the Merriam Webster dictionary explains it as "by, on, or across land" so that we think that its meaning is not specific to above or below surface.

Referee #3 comment: "_ varying from 0.07 to 0.24" what kind of land surfaces are these appropriate for? igneous rock? desert sand?

Authors' response: *Vegetated surfaces, but also deserts with mainly rocky surfaces have albedo values within this range. Sandy deserts typically have higher albedo values.*

Referee #3 comment: Page 3, line 32. While the surface temperatures reach equilibrium quickly for dry planets, what about the atmosphere-land water balance? It is my understanding that in some models it can take a considerable amount of model time for water to permeate out of the sub-surface aquifer.

Authors' response: *Referee#3's remark "it can take a considerable amount of model time for water to permeate out of the sub-surface aquifer" is indeed valid in the case of a geological reservoir on a real planet where recycling does have long internal timescales and the equilibration of surface temperature may require a considerably longer time than spanned by our simulations. However, the sub-surface reservoir that we consider in our study just refers to the bottom two layers of the soil. The total soil depth in our study is about 10 meters of which the layers below a depth of 1.2 meters are almost completely filled with water homogenously all over the globe and should not be misunderstood as a geological reservoir. Only the top three layers of the soil are dynamic which take around three years to equilibrate.*
We added this explanation to the methods section.

Referee #3 comment: It would be interesting to see a figure similar to figure 5, but showing the integrated water vapor column amount, the integrated cloud water amount, and the integrated cloud fraction.

Authors' response: *As requested, we show in figure 5 below the vertically integrated water vapor column amount, vertically integrated cloud water amount, and vertically integrated cloud fraction for different stages of the transition from the HD state to the CW state similar to figure 5 in the original manuscript.*

In the HD state, the lower latitudes are mainly covered by high cloud cover (Fig. 2) with very low liquid water content and huge amount of water vapor in the atmosphere.

Stage 1: *Once the albedo is increased beyond the threshold, precipitation clusters start to appear close to the equator, more rain reaches the surface filling up the dry uppermost soil layers in the lower latitudes. With increased soil moisture availability, evapotranspiration increases resulting in a*

transient increase in atmospheric water vapor content and cloud liquid water content in the lower latitudes (Fig. 5).
Stage 2 & 3: *As the temperature drops further in the later stages, water vapor saturation limit and the height at which clouds can form is lowered leading to an increase in low level cloud cover with high liquid water content at the lower latitudes. Increase in low level cloud cover increases the planetary albedo and results in the rapid cooling of the surface and a decrease in atmospheric water vapor content and eventual stabilization of the CW state.*

Referee #3 comment: It would be interesting to see additional panels on figure 7 showing cloud and TOA albedo, and also the greenhouse effect. You can estimate the greenhouse effect as G=sigma*Ts^4 – OLR

Authors' response: *As requested, we show in figure 6 below cloud albedo, TOA albedo, and greenhouse effect as a function of background soil albedo similar to Figure 7 in the original manuscript. We notice that for an increase in background soil albedo, the planetary albedo increases due to an increase in low level cloud cover at lower latitudes.*

Also, at a higher background soil albedo, the greenhouse effect is much lower compared to that for lower background soil albedo due to decrease in atmospheric water vapor greenhouse warming (Fig. 6c).

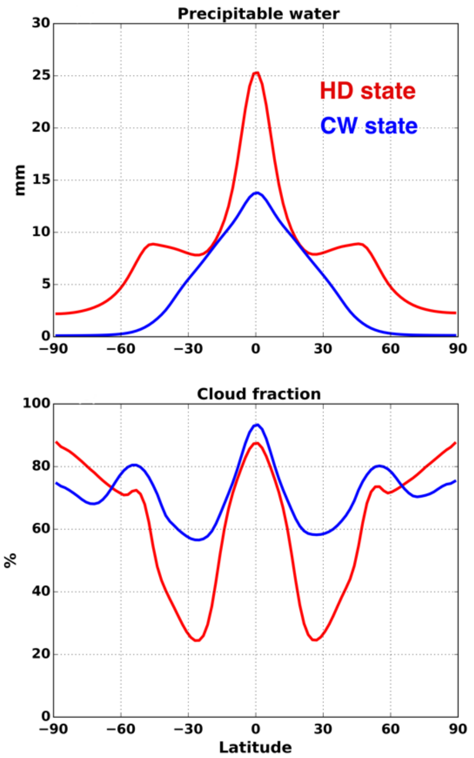

Figure 1: Annual mean meridional profiles of precipitable water (top panel) and cloud cover fraction (bottom panel) for the two terra-planet states: HD (α = 0.14) and CW (α = 0.15) in the simulations Z14 and Z15 averaged over a period of ten years.

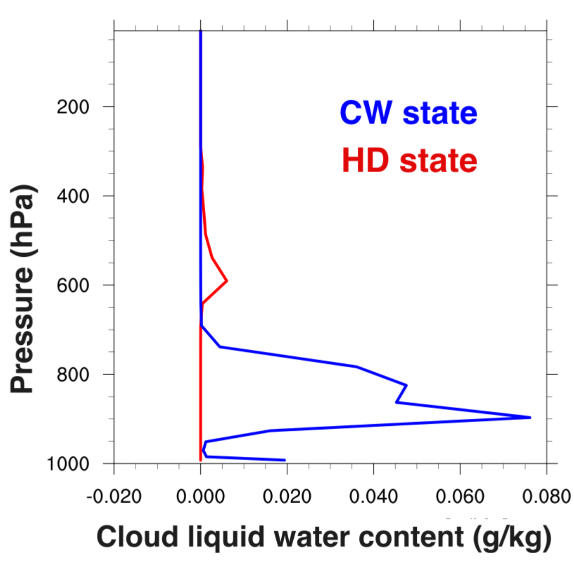

Figure 2: Vertical profiles of cloud liquid water content (g kg^{-1}) and cloud area fraction for the two terra-planet states in the simulations Z14 and Z15 averaged over a period of ten years.

Simulations	Background soil albedo	Surface roughness	Heat capacity	Snow albedo	Water reservoir depth from the surface
Aqua-planet	0.07	Ocean	Ocean	0.07	50 m slab ocean, no heat transport
Swamp1	0.07	Ocean	Ocean	0.07	Constant ground water table at a depth of 0.3 m
Swamp2	0.07	Land	Land	0.07	Constant ground water table at a depth of 0.3 m
HD	0.07-0.14	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m
CW	0.15-0.24	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m

Table 1. Summary of simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

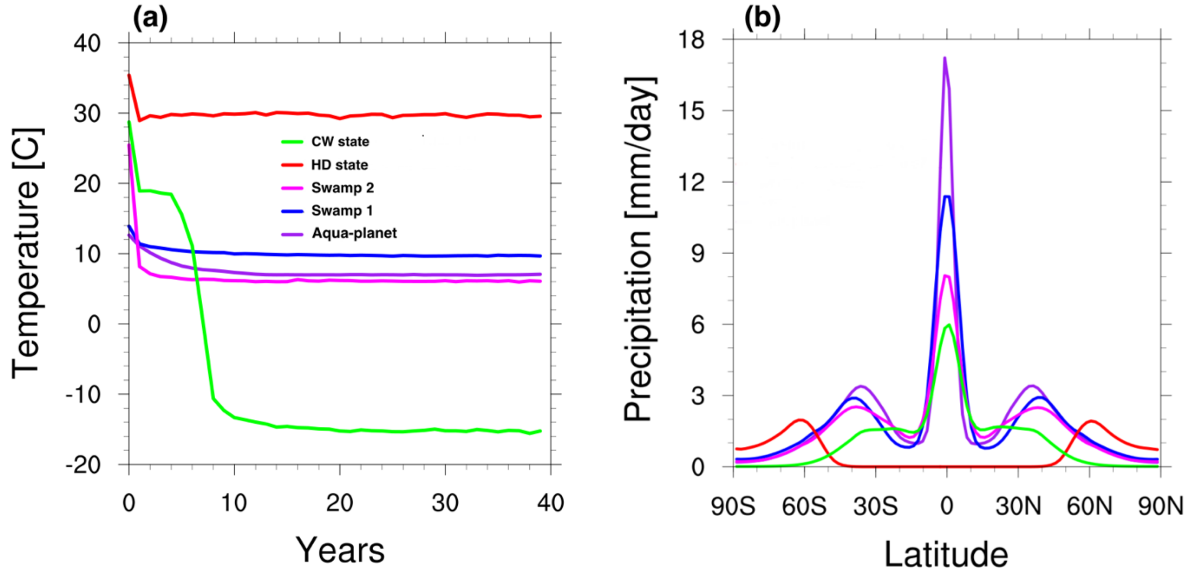

Figure 3: (a) Time series of global mean surface temperature (°C) and (b) annual mean meridional profile of precipitation (mm day^{-1}) for different simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

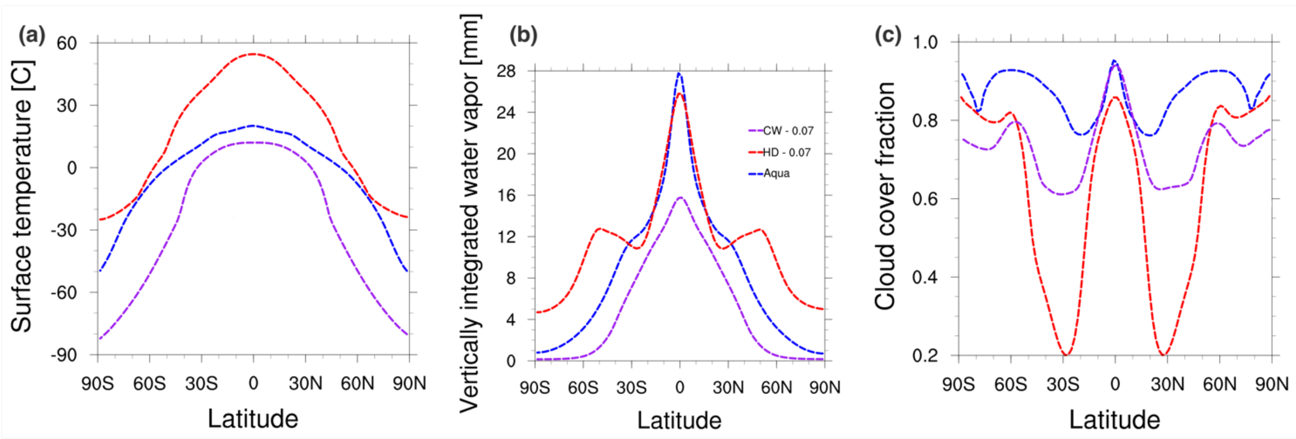

Figure 4: Annual mean meridional profiles of (a) surface temperature (°C), (b) vertical integrated water vapour (mm), (c) cloud cover fraction for an aqua-planet simulation with albedo = 0.07 and terra-planet simulations with the same background soil albedo value (0.07) but initialized differently: from a warmer state (HD – 0.07 simulation) and from a colder state (CW - 0.07 simulation).

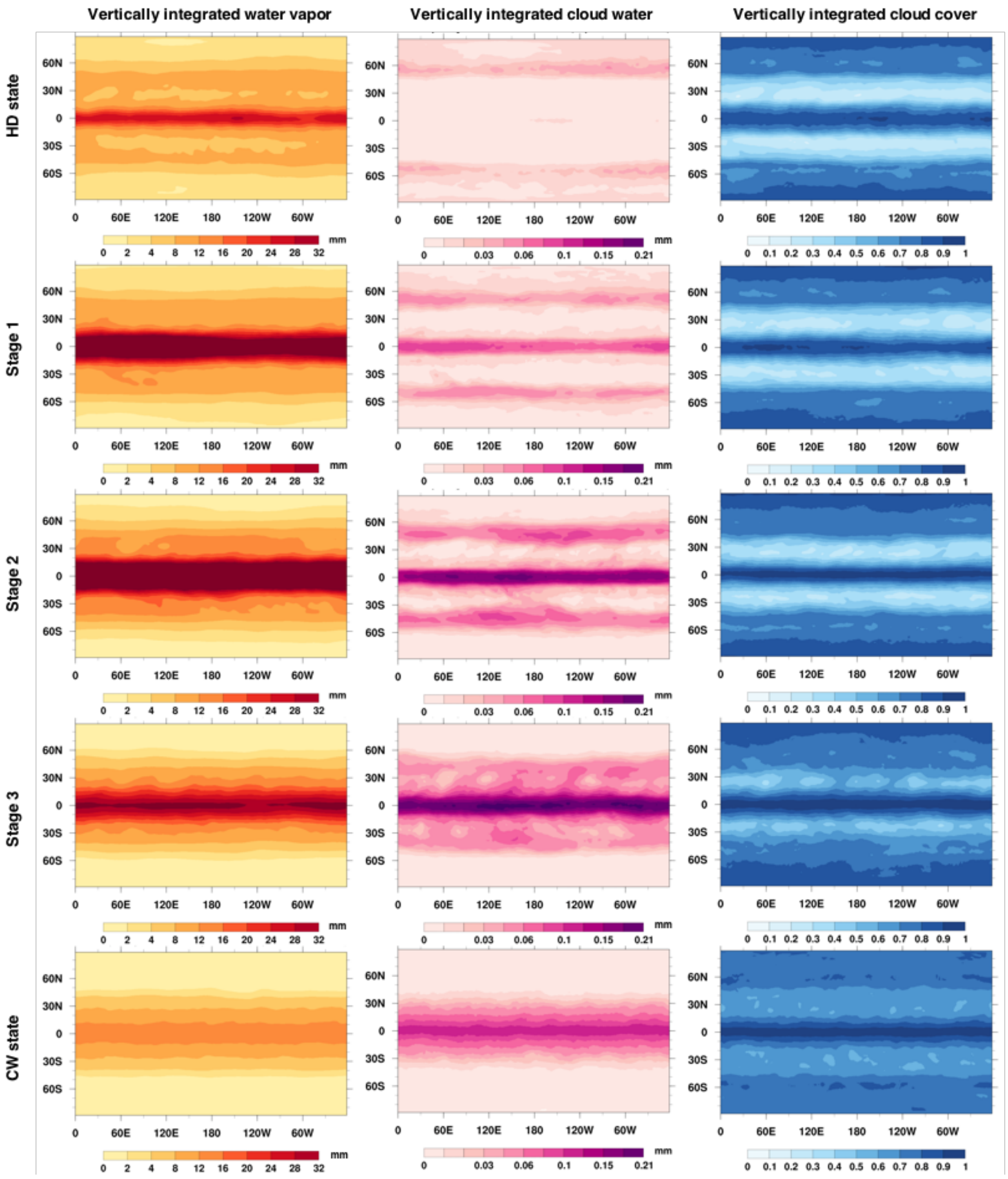

Figure 5: Annual mean vertically integrated water vapor (left panels), vertically integrated cloud water (centre panels) and cloud cover cover fraction (right panels) for different stages of the transition (TRANS simulation) from the HD state to the CW state similar to the Fig. 5 in the original manuscript.

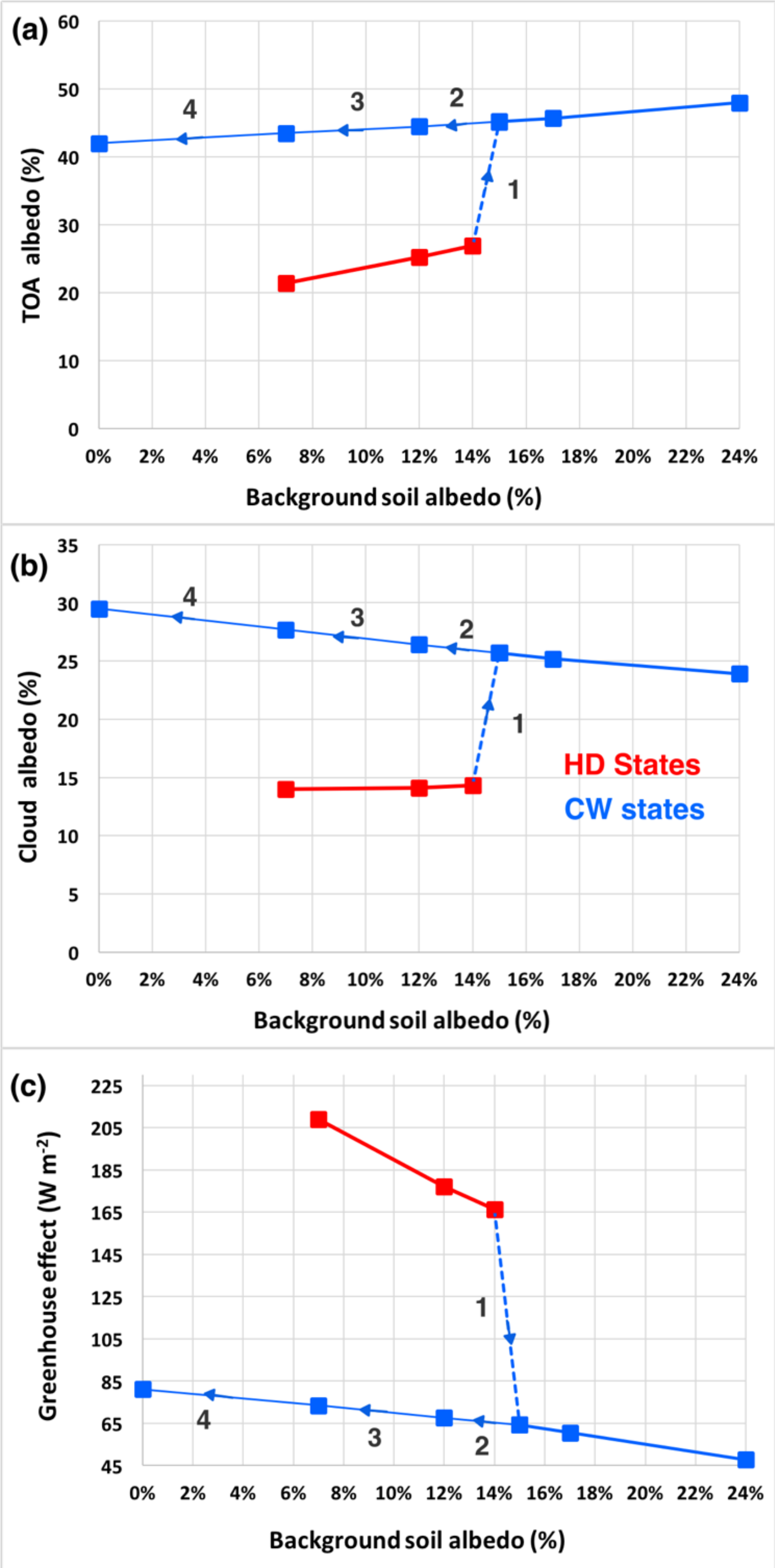

Figure 6: TOA albedo (a), cloud albedo (b) and Greenhouse effect (c) plotted as a function of background soil albedo (α). Path 1 denotes the spontaneous transition from the HD to the CW state when increasing background soil albedo and paths 2, 3 and 4 denote the reverse state development upon stepwise lowering of background albedo starting from the threshold value (α = 0.15) to α = 0.

Two drastically different climate states on an Earth-like terra-planet

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Abstract. We study an Earth-like terra-planet (water limited terrestrial planet) with an overland recycling mechanism bringing fresh water back from the high~~er~~ latitudes to the low~~er~~ latitudes. By performing model simulations for such a planet we find two drastically different climate states for the same set of boundary conditions and parameter values: A Cold and Wet (CW) state (present-day Earth-like climate) with dominant low-latitude precipitation and, a Hot and Dry (HD) state with only high-latitude precipitation. We notice that for perpetual equinox conditions, both climate states are stable below a certain threshold value of background soil albedo while above the threshold only the CW state is stable. Starting from the HD state and increasing background soil albedo above the threshold causes an abrupt shift from the HD state to the CW state resulting in a sudden cooling of about 35°C globally which is of the order of the temperature difference between the present-day and the Snowball Earth state.~~. Also, hen~~ When albedo in the CW state is reduced ~~back~~ down to zero the terra-planet does not ~~display a~~ shift back to the HD state (no closed hysteresis). This is due to the high cloud cover in the CW state hiding the surface from solar irradiation~~. As a result, this reduction of background~~ so that surface albedo has only a minor effect on the top of the atmosphere radiation balance~~, thereby making it impossible to heat the planet sufficiently strongly to switch back to the HD state~~. Additional simulations with present day Earth's obliquity all lead to the CW state, suggesting a similar abrupt transition from the HD state to the CW state ~~for non-zero obliquity~~ ~~which is the only stable state in this configuration~~ when increasing obliquity from zero. Our study also has implications for the habitability of Earth-like terra-planets. At the inner edge of the habitable zone, the higher cloud cover in the CW state cools the planet and may prevent the onset of a runaway greenhouse state. At the outer edge, the resupply of water at low~~er~~ latitudes stabilizes the greenhouse effect and keeps the planet in the HD state and may prevent water from getting trapped at high~~er~~ latitudes in frozen form. Overall, the existence of bi-stability in the presence of an overland recycling mechanism hints at the possibility of a wider habitable zone for Earth-like terra-planets at lower obliquities.

1 Introduction

Recent advancements in observational astrophysics like with the Kepler mission led to the discovery of a vast number of potentially habitable planets (Kopparapu et al. 2014). Habitable planets are planets which can maintain liquid water on their surface (Hart, 1978; Kasting et al., 1993; Kopparapu et al., 2014). The habitability of a planet is influenced by several factors like stellar flux, orbit and planetary properties (Schulze-Makuch et al., 2011). In the case of Earth-like planets, it has been shown that the width of the habitable zone strongly depends on the water cycle and the carbonate-silicate cycle (Kasting et al., 1993; Kopparapu et al., 2013; Zsom et al., 2013). This is because, these cycles control the atmospheric concentration of water vapour, carbon-di-oxide and surface pressure of a planet. In our study, we focus on the role of the water cycle.

The water cycle on a planet strongly depends on the amount of surface water present which is controlled by a complex interplay between processes like atmospheric circulation, precipitation and cloud formation. Depending on the amount of surface water, habitable planets fall into two classes: aqua-planets – planets covered with global oceans – and terra-planets – planets with vast deserts or vegetated surfaces and a limited amount of water (Dune, Herbert, 1965; Abe et al., 2005, 2011, Leconte et al., 2013). In the present study, we investigate the climate of an Earth-like terra-planet for low obliquities.

Over the recent years, there has been a growing interest in the study of terra-planets due to three reasons: First, the absence of oceans on a terra-planet helps to isolate the effects of land surface processes and thus aids in better understanding of the land-atmosphere coupling (Aleina et al., 2013; Rochetin et al., 2014; Becker and Stevens, 2015). Second, terra-planets with optically thin atmospheres (like present day Earth's atmosphere) can maintain their inner edge of the habitable zone much closer to their parent star compared to aqua-planets ~~due to their higher surface albedo (Abe et al., 2011;~~ (Zsom et al., 2013). The reason is that limited atmospheric access to water results in a dry climate with water confined to the high latitudes for lower obliquities (Abe et al., 2005; Abe et al., 2011; Leconte et al., 2013). In such dry climates, the water vapour feedback is severely muted and the greenhouse warming is substantially lowered which allows dry planets to maintain habitability even at higher stellar fluxes (Zsom et al., 2013). Third, terra-planets at lower obliquities can support a wider habitable zone compared to that of aqua-planets (Abe et al., 2011)~~. ~~because the dry atmosphere of terra-planets limits the escape of hydrogen molecules and shows a higher resistance to the runaway greenhouse effect. Also, the dry atmosphere inhibits the formation of clouds, ice and snow and thus helps the planet to resist complete freezing (Abe et al., 2011; Leconte et al., 2013). However, the habitable areas on such a dry planet are confined to the edges/bottom of frozen ice caps (Leconte et al., 2013; Zsom et al., 2013). Whether at such edges liquid water can exist sufficiently permanent for life to evolve and persist is unclear (Zsom et al., 2013). Recycling mechanisms similar to those which occur on the present day Earth like ocean circulation and surface runoff must exist to maintain a long-lasting liquid water inventory. Leconte et al., 2013 argue that on dry planets, mechanisms like gravity driven ice flows and geothermal flux can maintain sufficient amounts of liquid water at the edges/bottom of large ice caps. The liquid water thus formed can eventually flow back to the lower latitudes to be re-available for evaporation. However, there exists no climate modelling study on an Earth-like terra-planet which actually implements either implicitly or explicitly such a recycling mechanism bringing fresh water back from high to low latitudes. In our study, we consider an Earth-like terra-planet with an unlimited subsurface water reservoir as a way to mimic the recycling mechanism. Even though the water reservoir in our case is unlimited, it is not similar to an aqua-planet because it includes additional resistances which restrict atmospheric access to water (i.e. soil and plant resistances along with aerodynamic resistance).

Evidence from paleo-climate modelling studies reveals that planets within the habitable zone can support multiple climate states but all of these states may not satisfy the stable liquid water on their surface. Like our Earth can exist in two different climate states – the present day warm state with abundant surface liquid water and the Snowball Earth state with no surface liquid water (Marotzke and Botzet, 2007; Voigt and Marotzke, 2010; Voigt et al., 2011). Recent studies on the habitability of aqua-planets also indicate that the presence of multi-stability can further complicate the interpretation of habitability of Earth-like planets (Linsenmeier et al., 2015; Boschi et al., 2013; Lucarini et al., 2013). With our study we demonstrate that under certain conditions Earth-like terra-planets exhibit two drastically different climate states and both these climate states can support habitable areas with long-lived surface liquid water.

It should be noted that the present paper is mainly descriptive in nature and is not meant to give a detailed explanation explain of the mechanisms for leading to the emergence of the two climate states and why transition happens between them.the way the transition between them happens This is still under investigation. The paper is organised as follows: Sect. 2 describes our model, our terra-planet configuration and gives an overview on the simulations performed for this study. Sect. 3 discusses the two drastically different terra-planet climate states at perpetual equinox conditions. Sect. 4 describes the transition between the two climate states. In Sect. 5 hysteretic behaviour is discussed. Sect. 6 explores the role of the snow albedo feedback for the emergence of the different climate states. Sect. 7 is about the terra-planet climate at present day obliquity. Sect. 8 draws some general conclusions from our study, in particular for the habitability of terra-planets.

2 Model and simulation setup

2.1 Model

We use the ICOsahedral Non-hydrostatic (ICON) General Circulation Model jointly developed by the MPI for Meteorology and the German Weather Service (DWD) and run it in terra-planet configuration i.e. with a single globally extended continent. The model has a horizontal resolution of R2B04 equivalent to a resolution of an evenly distributed rectangular grid of about ~ 160 Km and 47 layers in the vertical. The atmosphere model uses a non-hydrostatic dynamical core on an icosahedral-triangular Arakawa C-grid (Zangl et al., 2015), and the model atmospheric physics is similar to ECHAM6 physics (Stevens et al., 2013). The radiative transfer calculations are based on the Rapid Radiative Transfer Model (Mlawer et al., 1997; Iacono et al., 2008). Convection is parameterized by the mass flux scheme of Tiedtke (1989) with modifications to penetrative convection by Nordeng (1994). Cloud cover is calculated based on relative humidity (Lohmann and Roeckner, 1996). For a complete description of the model physics and parameterizations, the reader is referred to Stevens et al. (2013). The ICON version used in this study inherits the land physics from ECHAM5 (Roeckner et al., 2004) extended by a layered soil hydrology (Hagemann and Stacke, 2015).

2.2 Terra-planet configuration

The Terra-planet configuration is designed to be highly symmetric with no orography and glaciers. The rotation rate and the solar constant are the same as for the present day Earth. We consider two situations: perpetual equinox (zero obliquity) and present day Earth's obliquity (23.5°). Background concentration of CH_4, N_2O and aerosols are fixed to zero, while water vapor is prognostic and CO_2 concentration in the atmosphere is fixed to 348 ppmv. The ozone distribution is assumed to be zonally uniform and meridionally symmetric.

Land surface properties are assumed to be homogenous: Leaf Area Index (LAI) =3, surface roughness=0.05m. The albedo of snow over the land surface ranges between 0.4 - 0.8 depending on the surface temperature. We maintain the ground water table at constant depth of 1.2 m to mimic the recycling of water from higher to lower latitudes. The root depth and soil depth are both set to 6 m such that the roots always have access to the subsurface reservoir. By prescribing this subsurface water level thereby, the water cycle in the terra-planet

~~configuration is not closed i.e., the water drawn out of the subsurface reservoir by evapotranspiration in the low-latitudes gets accumulated near the higher latitudes but it does not return back to the low latitudes. Our terra-planet setup closely resembles that of recent 3-dimensional studies (Abe et al., 2011; Leconte et al., 2013) on Earth-like terra-planets except that those studies did not consider an overland water recycling pathway bringing back water from higher to lower latitudes that we mimic by the prescribed subsurface water reservoir.~~ The total soil depth in our study is about 10 meters (m) of which the layers below a depth of 1.2 m are forced to be filled permanently by at least 90% with water homogenously all over the globe. We refer to these bottom two layers of the soil in our study as 'subsurface reservoir' which should not be confused with a geological reservoir operating at timescales much longer than the soil hydrological timescales. The root depth is fixed to 6 m such that the roots always have access to this subsurface reservoir. Leaf Area Index (LAI) is set to a value of 3. This value controls how much surface in a grid cell participates in transpiration, while the rest exhibits bare soil evaporation. LAI and root depth are not considered as a representation of vegetation but only as a technical means to parameterize the atmospheric access to water like other hydrological parameters of the model, e.g. soil porosity or hydraulic conductivity. The albedo of snow ~~over the land surface~~ ranges between 0.4 - 0.8 depending on the surface temperature. Surface roughness is fixed to 0.05 m.

By the introduction of the subsurface reservoir we implicitly equip our planet with a very efficient recycling mechanism shuffling water back from sink regions (P-E > 0) to source regions (P-E < 0). This can be understood as follows. In sink regions water either piles up as snow or is lost as runoff. But since neither snow height nor runoff affect the climate in our simulations, the global amount of water relevant for the physical climate stays constant for a stationary state. Accordingly, considering only this 'effective' water, the amount of water added to the subsurface reservoir equals the water lost in the sink regions. For this reason, we can interpret the permanent refilling of the subsurface reservoir to mimic a very efficient recycling of water from sink to source regions.

Representing overland water recycling by a homogenously filled subsurface reservoir is indeed an idealization. In fact, recycling may occur at different speeds and thereby is less or more effective than what we consider in our study. Based on the speed of recycling, the water level of this subsurface reservoir would vary from what is considered in our study. It should be noted that the choice of water level of the subsurface reservoir considered in our study (1.2 m) is not arbitrary, but a result of a sequence of simulations, where we explored the continuum between an aqua and a terra planet (see Appendix A).

Our terra-planet setup closely resembles that of recent 3-dimensional studies (Abe et al., 2011; Leconte et al., 2013) on Earth-like terra-planets except that those studies did not consider an overland water recycling pathway bringing back water from high~~er~~ to low~~er~~ latitudes that we mimic by the prescribed subsurface water reservoir.

2.3 Simulations

We study the effect of background surface albedo (α) on the climate in a series of simulations with α varying from 0.07 to 0.24 at perpetual equinox (0°) (Z7 to Z24 simulations in Table 1) and at present day conditions (23.5°) (S7 to S24 simulations in Table 1). All these simulations start from the same initial atmospheric state with a homogenous temperature, 290 K and moisture content, 25 kg m^{-2}. Due to the small thermal inertia of the land surface and the atmosphere, the simulations reach a steady state within 10 years. We continue the simulations for additional 30 years of which, the last 10 years are used in the analysis of the mean climate. To see the transition between different climate states at the perpetual equinox condition more clearly, we perform an additional simulation (TRANS). First, we simulate the planet in the stable Hot and Dry (HD) state for 30 years for $\alpha = 0.14$ and then increase α abruptly to $\alpha = 0.14 + 0.01$ corresponding to the Cold and Wet (CW) state and continue the simulation for another 30 years. Then, to check for hysteresis, we continue the TRANS simulation by switching the albedo back to 0.14 and continued lowering α stepwise until zero. Additionally, to test the sensitivity of the climate states to model parameterizations, we performed simulations with a different convection scheme at perpetual equinox conditions (T7 to T24 simulations). Finally, to investigate the role of snow-albedo feedback on the terra-planet climate states, the terra-planet is simulated with dark snow (DS simulations in Table 1) (i.e. we assume snow albedo to be same as background surface albedo). The details of all terra-planet simulations are listed in Table 1.

3 Drastically different climate states

Figure 1 shows the time evolution of global mean surface temperature and precipitation for different terra-planet simulations at zero obliquity (Z7 to Z24 simulations). We notice that the terra-planet exists in two drastically different climate states: a Hot and Dry (HD) state for $\alpha < 0.15$ and a Cold and Wet (CW) state for $\alpha \geq 0.15$. This is different to findings in previous studies (Abe et al., 2005, 2011; Leconte et al., 2013) on low obliquity terra-planets who found only the HD state. The mean climate in the two states is remarkably different (Fig. 2).

3.1 Surface Temperature

The annual mean surface temperature in the CW state is below freezing point almost everywhere, except in the low-latitudes where it is around 10°C. High cloud cover (Fig. 2e) and a high planetary albedo (Fig. 2f) lower the surface absorption of incoming radiation and result in very low temperatures in the CW state. On the other hand, in the HD state, the global mean surface temperature is about 35°C higher than in the CW state.

3.2 Precipitation

Besides temperature, the other striking difference between the two states is the location of precipitation bands on the planet. In the HD state, no precipitation occurs in the low-latitude region between 40°S to 40°N. Only latitudes higher than 40° receive some amount of rainfall (Fig. 2b) (compare Abe et al., 2005, 2011; Leconte et al., 2013). In contrast, in the CW state, the precipitation and cloud cover are mainly concentrated in the low~~er~~ latitudes with a banded structure similar to the present day equatorial Inter-Tropical Convergence Zone (ITCZ). The reason for the absence of CW state in previous studies is the lack of an effective mechanism that can recycle water trapped at the high~~er~~ latitudes in the form of snow and ice back to the low~~er~~ latitudes.

3.3 Feedbacks that keep HD State dry and CW State wet

Figures 2c and d show the distribution of water on the planet. In the HD state, the very high temperatures in the low latitudes raise the water vapour saturation limit and the moisture-holding capacity of the atmosphere allowing the planet to store a substantial amount of its water in the atmosphere (Fig. 2c). Also, due to huge amounts of net radiation at the surface in the HD state, the uppermost soil layers in the low latitudes dry out quickly. Dry uppermost soil layers imply small evaporation leading to no precipitation which in turn leads to even less evaporation. This self reinforcing mechanism in the HD state always maintains very dry upper soil layers in the low latitudes (Fig. 2d). On the whole, supressed precipitation at low latitudes along with a nevertheless permanent export of moisture away from the low latitudes result in water to be mainly present at high latitudes in the HD state. On the other hand, in the CW state, the lower annual mean temperatures in the low latitudes facilitate condensation and precipitation and minimise the moisture content of the atmosphere (Fig. 2c). Thus, continuous precipitation at low latitudes in the CW state, keeps the upper soil layers in the low latitudes always wet (Fig. 2d) thus providing by evaporation sufficient water for a stable precipitation regime in the low latitudes.

3.4 Feedbacks that keep HD State hot and CW State cold

The vertical distribution of cloud cover and cloud water content in the low latitudes for the two terra-planet states is displayed in Figure 3. For the HD state, the cloud cover in the low latitudes is exclusively composed of high level clouds (Fig. 3). The reason is, the higher water vapour saturation limit of the atmosphere in the HD state raises the height at which condensation and cloud formation occurs. High clouds with very low liquid water content are more transparent to shortwave radiation, at the same time they reduce outgoing longwave radiation and thereby warm the planet. Moreover, hotter temperatures in the HD state lead to moister atmosphere (Fig. 2c) and in turn stronger greenhouse warming. Overall, high clouds in the low latitudes along with higher water vapour greenhouse warming keep the planet always hot and stabilize the HD state. Instead, in the CW state, the cloud cover in the low latitudes is mainly comprised of low level clouds (Fig. 3) due to lower water vapour saturation limit of the atmosphere. Low clouds with high liquid water content cool the planet as they increase the planetary albedo. Also, lower temperatures in the CW state lead to a drier atmosphere (Fig 2c) and a weaker water vapour greenhouse warming. On the whole, low clouds together with weaker greenhouse warming always keep the planet cool and stabilize the CW state.

3.5 Mean Circulation and energy transport

The mean circulation pattern for the two climate states is shown in Fig. ~~3~~4a, b. We notice that in both the states, the circulation pattern resembles the present-day hemispheric three cell structure. But when comparing the two states, the width and intensity of the circulation are very different: ~~The Hadley cell is narrower and less intense in the CW state compared to a wider and a more vigorous circulation in the HD state~~ In the HD state, the Hadley cell is more vigorous and gets slightly wider with height (when measured around 500hPa) compared to that in the CW state. The neutrally stable atmospheric conditions in the HD state require larger mass flux to transport away heat and to stabilise the equatorial temperatures and hence support a more vigorous circulation (Held and Hou 1980; Caballero et al. 2008; Mitchell et al., 2008). Additionally, we notice that the circulation centre of the Hadley cell is very different in the two states (depicted by black arrows in Fig. ~~3~~4 a,b). The HD state has its circulation centre much closer to the surface at about 750 hPa, while in the CW state the centre is much higher at 500 hPa.

Observations and modelling studies in the literature also report intense low centred circulations for present day Earth's climate in the tropical eastern pacific during the northern hemisphere summer time (Zhang et al. 2004, 2009; Nolan et al., 2007), for a Snowball Earth state (Pierrehumbert, 2005) and for Titan (Mitchell et al., 2006, 2009). These circulations have the tendency to export larger amounts of moisture out of the low~~er~~ latitudes compared to high centred circulations. We also notice this increased transport of moisture away from the low latitudes with the more vigorous low centred Hadley cell in the HD state compared to that in the CW state (Fig.

~~3~~4c). The reason is, in the CW state the existence of deep convection allows moisture to reach much higher elevations before getting exported to high~~er~~ latitudes (Nolan et al., 2007). At higher elevations, more moisture can condense and be lost as precipitation due to lower temperatures and much less remains for being exported away. Instead, in the HD state the lack of precipitation allows more moisture to be exported.

Figure ~~4~~5 shows the northward transport of energy (transport due to latent and sensible energy) by atmospheric circulation in the two climate states. For the CW state, latent energy transport is equatorward in the low latitudes and poleward in the mid latitudes. In contrast, in the HD state latent energy is exported poleward at all latitudes (latent energy curves in Fig. ~~4~~5). The reason for the opposite sign in the low latitudes is that in the CW state (as in the case of present day Earth) intense precipitation dries out the atmosphere and thus keeps most of the water within the low~~er~~ latitudes limiting its poleward export (Fig. ~~3~~4c) – hence the net flow is always equatorward. Instead, in the HD state, by the absence of precipitation, moisture is retained in the air so that it is exported poleward.

The sensible energy transport in the HD state is considerably larger as compared to that in the CW state (Fig. ~~4~~5) despite of a lower equator to pole temperature gradient. This implies that the atmospheric circulation is more efficient in transporting the sensible energy to the higher latitudes. Overall, the net northward transport of energy is dominated by the sensible energy transport and is enhanced in the case of HD state. Further, the larger northward transport of energy in the HD state results in a smaller equator to pole temperature gradient compared to the CW state.

4 Transition to the CW state

Starting from the HD state ($\alpha = 0.14$), we abruptly increase the albedo to $\alpha = 0.14 + 0.01$ (simulation TRANS) and thereby initiate a shift to the CW state. The full transition from the HD state to the CW state takes about 4 years. The changes in annual mean surface temperature, precipitation, ~~while changes in mean circulation are shown in Fig. 6. an~~snow cover and mean circulation during the course of transition are shown in Fig. ~~5~~ 6. One can distinguish three transitional stages:

Stage 1: After the abrupt increase in α, small precipitation clusters appear in the low-latitude region and the terra-planet starts to cool down due to an increase in cloud cover and planetary albedo. Snow cover at high~~er~~ latitudes starts to increase slowly. The mean meridional circulation structure changes – small circulation cells appear very close to the equator. This happens for a period of one year.

Stage 2: The precipitation clusters aggregate into a band of deep convection around the equator accompanied by a sharp increase in precipitation. At this point, we still see precipitation bands even at high~~er~~ latitudes around 50°. However, the precipitation intensity at high~~er~~ latitudes is smaller (around 6 mm day^{-1} lower) compared to the precipitation at the equator. Surface temperature drastically decreases and the circulation structure is now associated with two cells, a shallow cell close to the equator and a deep cell slightly away from the equator.

Stage 3: Precipitation bands at the high~~er~~ latitudes start moving equatorward and precipitation intensity decreases compared to the previous stage. Surface temperature decreases further. Snow cover further increases and starts moving towards the equator. The circulation is now less intense with circulation centre around 500hpa.

Finally, the CW state is reached. Precipitation only occurs at low latitudes. Surface temperature is below freezing almost everywhere on the planet except at the low latitudes. Snow cover reaches down to the 40° latitude.

5 Hysteresis

To further study the bifurcation structure, we investigated the hysteretic behaviour. Figure 7 shows the global mean surface temperature plotted as a function of α. The spontaneous transition from the HD to the CW state and the associated abrupt cooling is seen as path 1. Starting from the CW state and lowering back α stepwise below the threshold value until zero does not lead back to the HD state. The reason is that the high cloud cover present in the CW state hides the surface from solar irradiation. Therefore, a reduction of α has only a minor effect on the top of the atmosphere radiation balance so that thereby it is impossible to heat the planet sufficiently strongly to switch back to the HD state. This is true even when repeating these simulations taking snow albedo equal to background soil albedo (experiments DS; no figure shown). Thus, the planet remains in the CW state indicating that under the chosen conditions for the terra-planet setup the hysteresis is not closed (Fig. 7).

6 Does snow albedo feedback play a role for the emergence of the two climate states?

Changes in snow cover can lead to multiple climate states in the Earth system with drastically different global mean surface temperatures like the present day Earth and the Snowball Earth (Budyko 1969; Sellers 1969). In this case, the large temperature difference between the two states is caused by the positive snow-albedo feedback. In our study, we also notice such huge differences in global mean surface temperatures between the two terra-planet climate states (Sect. 3). In order to test whether the snow albedo feedback is responsible for the huge temperature difference in our study, we performed additional simulations where we changed the snow albedo to be equal to the background albedo of soil (simulations DS in Table 1). With the darker snow, we still find the two climate states (Fig. 8) and the spontaneous transition between them. ~~the two state~~ The existence of the bifurcation even in the simulations with dark snow implies that the snow-albedo feedback is not the cause for the existence of the two states. However, the snow albedo feedback does enhance the drastic temperature change in the bright snow simulations by around 12°C compared to the dark snow simulations. Preliminary analysis indicates that a combination of cloud and hydrological feedbacks leads to the bi-stability (refer Sect 3.3 and 3.4).

7 Terra-planet with seasonality

So far, we considered a planet without seasonality because obliquity was set to zero. Next, we investigate ~~how~~ the climate on a terra-planet chang~~es~~ing with a seasonal orbit taking present day Earth's obliquity of 23.5° (S simulations in Table 1). We find that with seasonality the HD state disappears and the terra-planet always stays in the CW state (Fig. 9). This is contrary to previous studies on terra-planets which show that terra-planets always exist in a warm state for obliquities lower than 30° (Abe et al., 2005, 2011). ~~We notice that, in the presence of the seasonal cycle the meridional structure of insolation changes drastically resulting in a weaker meridional temperature gradient compared to the situation without seasonal cycle (Fig. 9a). This avoids overheating and drying of the lower latitudes (Fig. 9d) and stabilises the planet in the CW state.~~ We hypothesize that for Earth-like obliquity, the bi-stability is lost due to the seasonal migration of the rain bands towards the low latitudes. The seasonal migration of rain bands facilitates seasonal rain in the dry low-latitude region. Since soil moisture has a memory lasting for several weeks to months this causes the top soil layers in the low latitudes to remain wet even during the dry season. Thus there is always soil moisture in the originally dry low-latitude region to allow for continuous evaporation and precipitation. And this probably destroys the HD state so that the planet is always self stabilized in the CW state. A more detailed study on the reasons behind the loss of bi-stability for non-zero obliquities is ongoing but beyond the scope of the present paper.

8 Discussion and Conclusions

So far terra-planets have been investigated for a wide range of planetary properties like mass, rotation rate, atmospheric composition and orbit. Here, we focus on climate simulations of a terra-planet with low obliquity (< 30°), flat orography, and otherwise Earth like conditions. An important difference to previous studies concerns the treatment of atmospheric access to water. Past studies on possible climates of terra-planets prescribed a limited water inventory, which for low obliquities leads to trapping of the water at high latitudes and stabilizing the planet in a state with no precipitation at low latitudes, similar to what we call in our study 'Hot and Dry' state. By contrast, in the present study we assume an unlimited subsurface water reservoir, which is still different from an aqua planet configuration (having also an unlimited water reservoir), because soil and plant resistances restrict the atmospheric access to soil water in addition to the restriction from aerodynamic resistance. For such an Earth-like terra-planet with restricted water access we find two drastically different climate states, a Hot and Dry (HD) state characterized by a hot climate with precipitation confined to high~~er~~ latitudes and a Cold and Wet (CW) state which is closer to present-day Earth's climate with precipitation mainly occurring at low~~er~~ latitudes and an intense cycling of water there. Compared to the other studies mentioned above, we find this additional CW state only, because we implicitly assume for our terra-planet a mechanism restoring water from the high~~er~~ latitudes to low~~er~~ latitudes, refilling sufficiently the subsurface water reservoir to maintain the very active low latitude water cycle in this state. The difference in global mean temperature between these two climate states is 35°C (with the same boundary conditions), which is in the same order of magnitude as the temperature difference between present day and the Snowball Earth climate (Pierrehumbert et al., 2011; Micheels and Montenari, 2008; Fairchild and Kennedy, 2007; Hoffman and Schrag, 2002).

Similar to the abrupt transition to a Snowball Earth state, for perpetual equinox conditions one of our terra-planet simulations also shows an abrupt transition, namely from the HD state to the CW state. These two states exist for low background surface albedo α, while for high α only the CW state is possible. The abrupt transition occurs when in the HD state α is increased beyond a particular threshold value. While the transition to the Snowball Earth is driven by the snow albedo feedback, ~~the transition in our study is mostly driven by the cloud albedo feedback, accompanied by huge changes in the global hydrological cycle, an increase in planetary albedo, and a complex reorganization of the circulation patterns.~~ preliminary analysis indicates that a combination of cloud and hydrological feedbacks give rise to the transition in our study. Moreover, we notice that in our setup the terra-planet exhibits an open hysteresis: even with background surface albedo reduced to zero it does not return back to the HD state. Additional terra-planet simulations with an obliquity as the real Earth all result in a CW state, hinting at another possible bifurcation from the HD to the CW state when the obliquity is increased to non-zero values~~, but further analysis is needed to confirm this~~.

Concerning the global water cycle, the HD and CW states share one important similarity. The planetary boundary layer at low~~er~~ latitudes is extremely dry in the HD state with relative humidity of about 15%. Clearly, trade winds can maintain such a dry boundary layer only if the water supply at the surface is sufficiently limited. However, without any evapotranspiration at the surface the Hadley Cell would dry out completely, loosing the greenhouse effect that sustains the high temperatures of the HD state. Furthermore, in the CW state, to keep the rain along the equator one also needs a considerable water supply in the low~~er~~ latitudes. In summary, both climate states are associated with a strong atmospheric transport of water from low~~er~~ to high~~er~~ latitudes, which has to be balanced by evapotranspiration at the low~~er~~ latitudes. Therefore, allowing for both states to be potentially realized under the same boundary conditions, on a real planet, mechanisms must exist that can continuously restore water back to low~~er~~ latitudes. Such mechanisms exist on each conceivable planet with low obliquity and water in the low~~er~~ latitudes. For present day Earth this happens via the oceans. For our terra-planet the water is stored in frozen form at higher latitudes like in the past glacial states of our Earth. The resupply of water may happen via processes like melting of glaciers, transport of ice by gravity flows and melting at the bottom of large ice caps due to high pressure and geothermal heat flux. This provides liquid water, which is brought back to the low~~er~~ latitudes by rivers (Abe et al., 2010; Leconte et al., 2013). Note that the huge differences in climate between these two states is primarily a consequence of the completely different functioning of the global hydrological cycle, so that the assumed recycling mechanism can be considered as an additional degree of freedom to the internal dynamics extending the range of possible terra-planet climates.

Our findings may have some relevance for estimates of the habitable zone for such Earth-like terra-planets. In the HD state liquid water is confined to the mid-latitudes (40°-50°) in both hemispheres, whereas in the CW state, there are sufficient precipitation and high enough temperatures for permanent liquid water at low latitudes (40°S - 40°N). Thus in both climate states life can potentially persist. At the outer edge of the habitable zone, the assumed resupply of water from high~~er~~ to low~~er~~ latitudes stabilizes the greenhouse effect, keeps the planet in the HD state and may prevent a situation with all water accumulated at the high~~er~~ latitudes in the frozen form. At the inner edge of the habitable zone, by this resupply the planet can maintain precipitation and high cloud cover at the equator in the CW state. Thereby, the planetary albedo is increased which cools the planet and may prevent the runaway greenhouse state with all the water well mixed in the atmosphere in the gas phase. On the whole, our study thus suggests that the presence of a mechanism which ~~can~~ recycles ~~fresh~~ water from the high~~er~~ latitudes back to the low~~er~~ latitudes and results, as described, in the two drastically different climate states and may extend the habitable zone of Earth-like terra-planets at lower obliquities. ~~But substantiation of this hypothesis would need further simulations.~~

Appendix A: Sequence of simulations that led to the terra-planet bi-stability

The bi-stability found in this study should not be mistaken as a result of a random experiment or a bug in the land surface model. The bi-stability was found by systematically modifying our global climate model starting from a "swamp configuration" until a "terra planet configuration". The respective simulations showed climate states that were plausible from the configuration changes. In the “Swamp configuration” our model is able to successfully reproduce the climate of an “Aqua-planet”. Starting from this setup, we sequentially changed different parameters like surface heat capacity, surface roughness, background soil albedo, snow albedo, and the level of the global subsurface water reservoir as well as the land surface schemes (soil hydrology) in our land surface model (Table A1). The bi-stability emerged when the water level of the subsurface reservoir was lowered to 1.2 m. In Table A1 the sequence of simulations is listed and in Fig A1 we show the resulting time evolution of temperature and the zonal structure of precipitation.

Appendix ~~A~~B: Sensitivity of the climate states to model convection scheme

To confirm that the two climate states of the terra-planet are not an artifact of convective parameterizations, we performed an additional simulation with a different convection scheme. By default, the model uses the Nordeng convection scheme (Nordeng 1994). We have replaced the default settings and simulated terra-planet simulations with the Tiedtke convection scheme (Tiedtke 1989) and we find the two drastically different climate states irrespective of the convection scheme (Fig. ~~A~~B1).

Competing interests. The authors declare that they have no conflict of interest.

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Simulations	Background soil albedo	Obliquity	Convection scheme	Snow albedo
Z7 – Z24	0.07, 0.12, 0.14, 0.15, 0.17, 0.24	0	Nordeng	Dynamic
S7 – S24	0.07, 0.12, 0.14, 0.15, 0.17, 0.24	23.5	Nordeng	Dynamic
TRANS	0.14 – 0.15 – 0.14 – 0.12 – 0.07- 0.00	0	Nordeng	Dynamic
T7 – T24	0.07, 0.12, 0.14, 0.15, 0.17, 0.24	0	Tiedtke	Dynamic
DS	0.07, 0.12, 0.14, 0.15, 0.17, 0.24	0	Nordeng	Constant at background soil albedo

Table 1. Summary of simulations performed in this study.

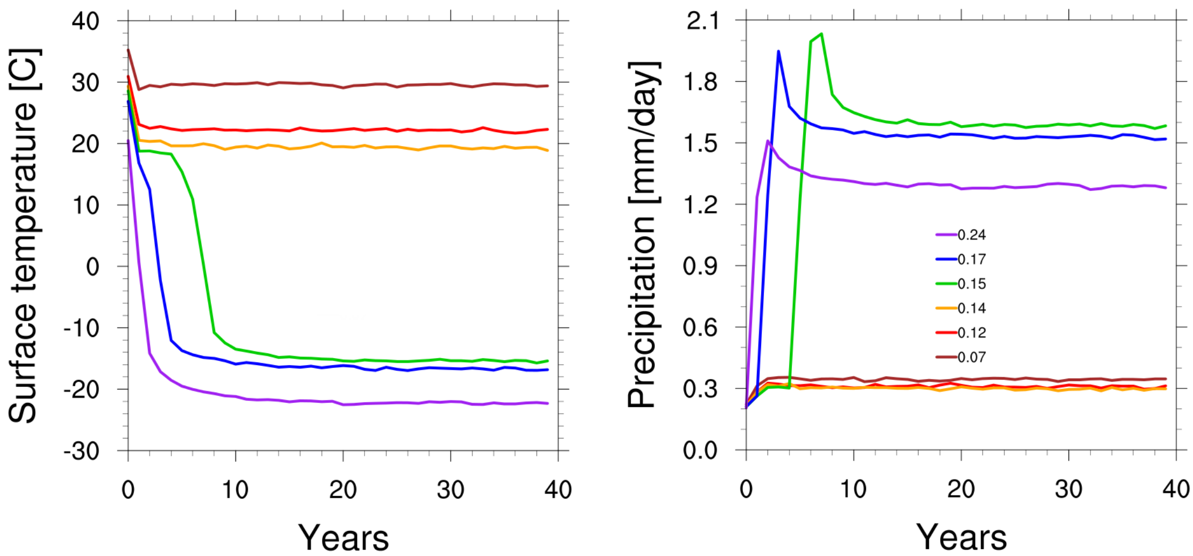


Figure 1: Time series of global mean surface temperature (°C) and precipitation (mm day^{-1}) for different background soil albedo values in the Z7- Z24 simulations.

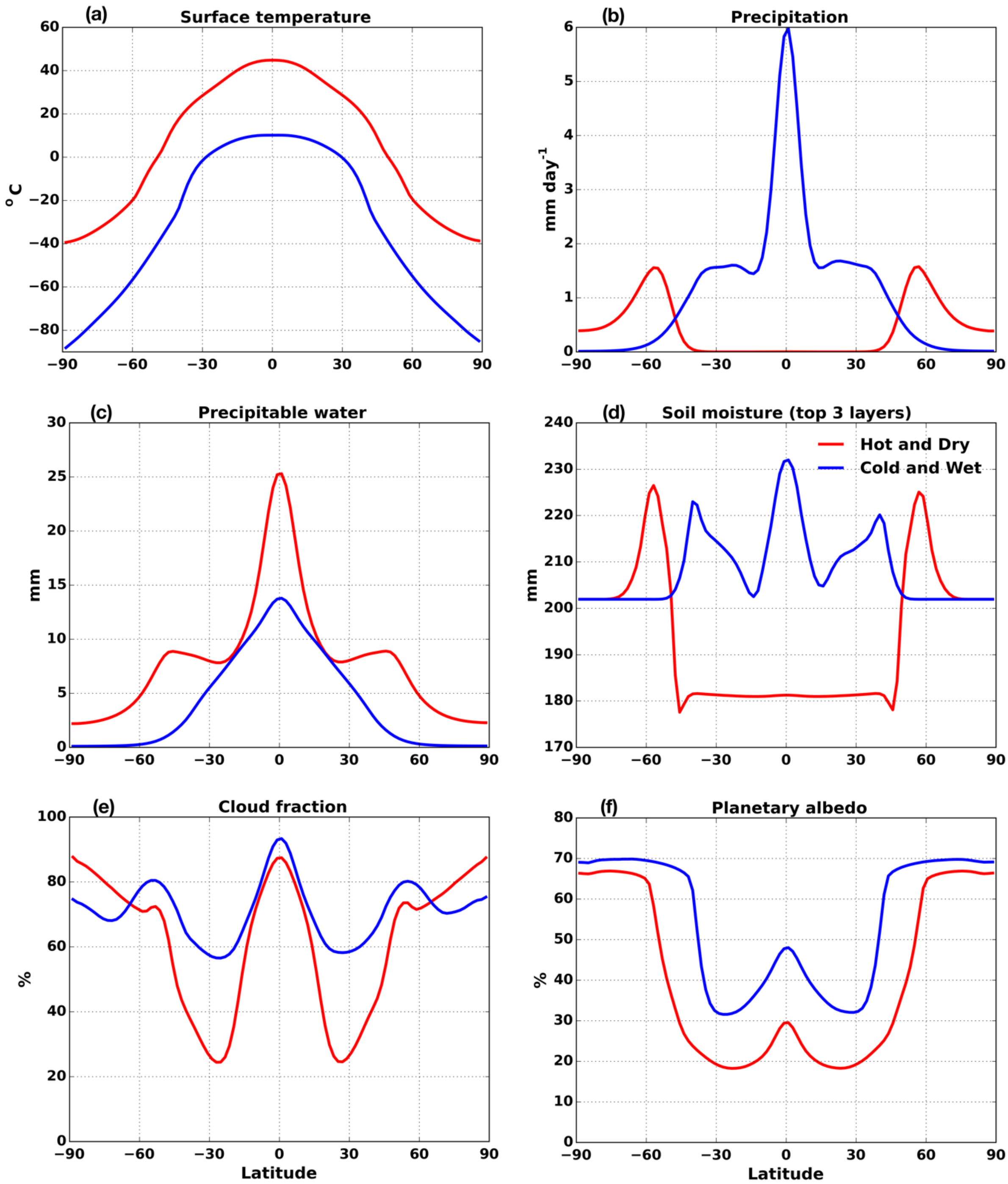
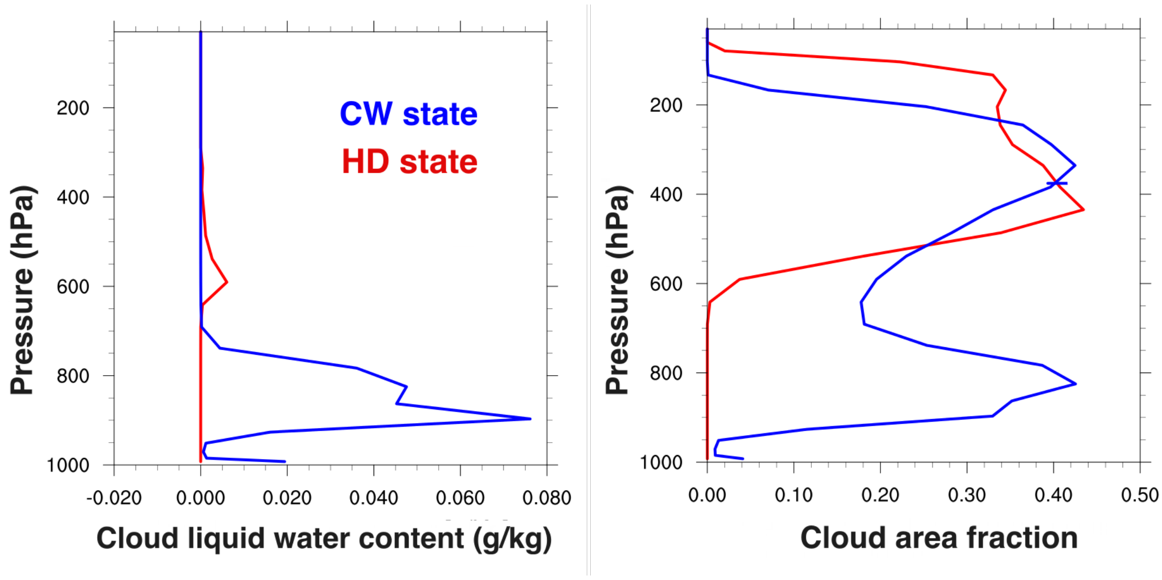


Figure 2: Annual mean meridional profiles of (a) surface temperature, (b) precipitation, (c) precipitable water, (d) soil moisture (averaged over the top three layers), (e) cloud fraction and (f) planetary albedo for the two terra-planet states: HD (α = 0.14) and CW (α = 0.15) in the simulations Z14 and Z15 averaged over a period of ten years.



5 **Figure 3: Vertical profiles of cloud liquid water content (g kg^{-1}) and cloud area fraction averaged over the low latitude region (30°S - 30°N) for the two terra-planet states in the simulations Z14 and Z15.**

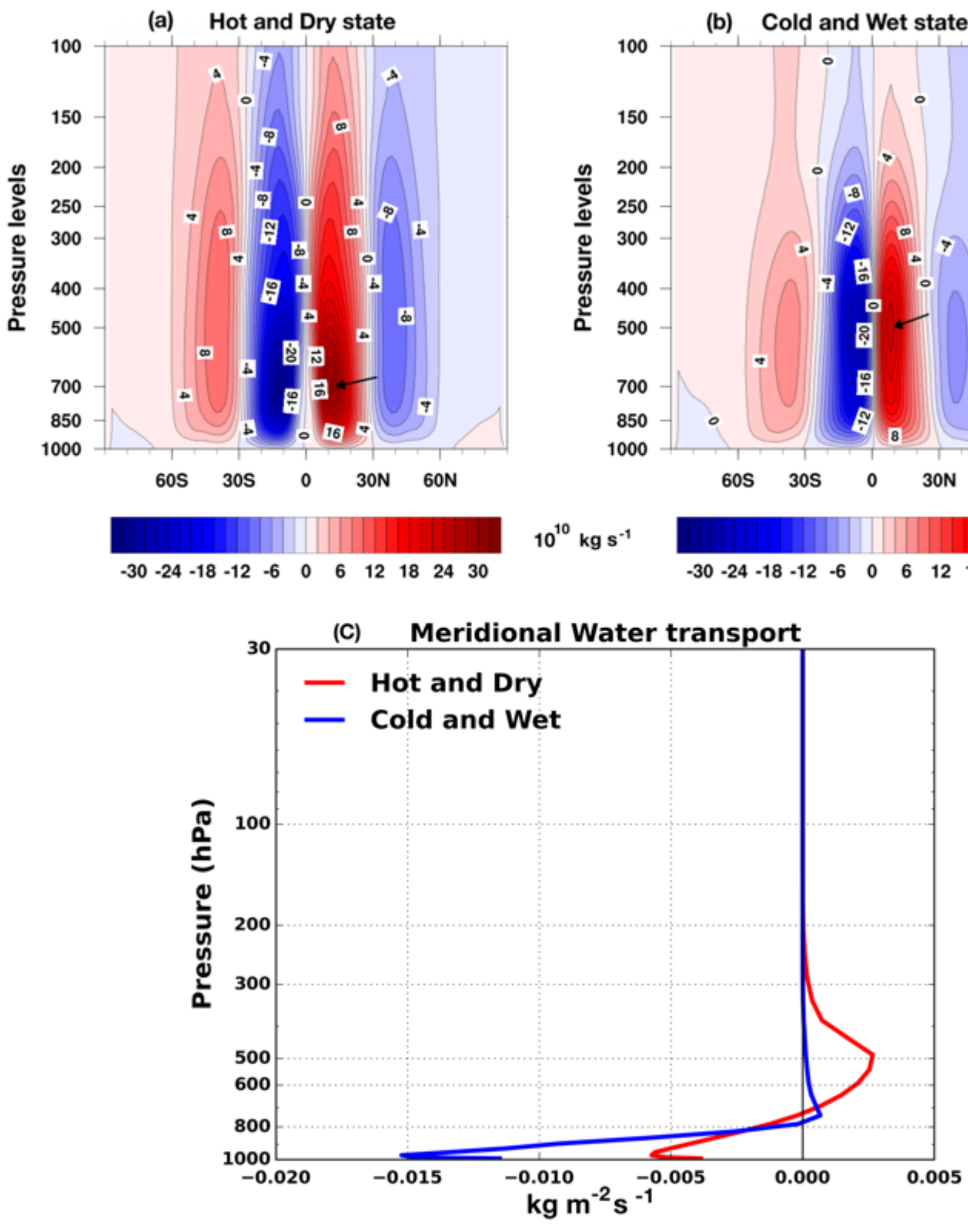


Figure ~~3~~4: Annual mean behavior of (a) and (b) meridional stream function in 10^{10} kg s^{-1}, (c) vertical profiles of meridional transport of water at 10°N for the two terra-planet states in the simulations Z14 and Z15 averaged over a period of ten years. The black arrows in (a) and (b) denote the northern Hadley circulation centre.

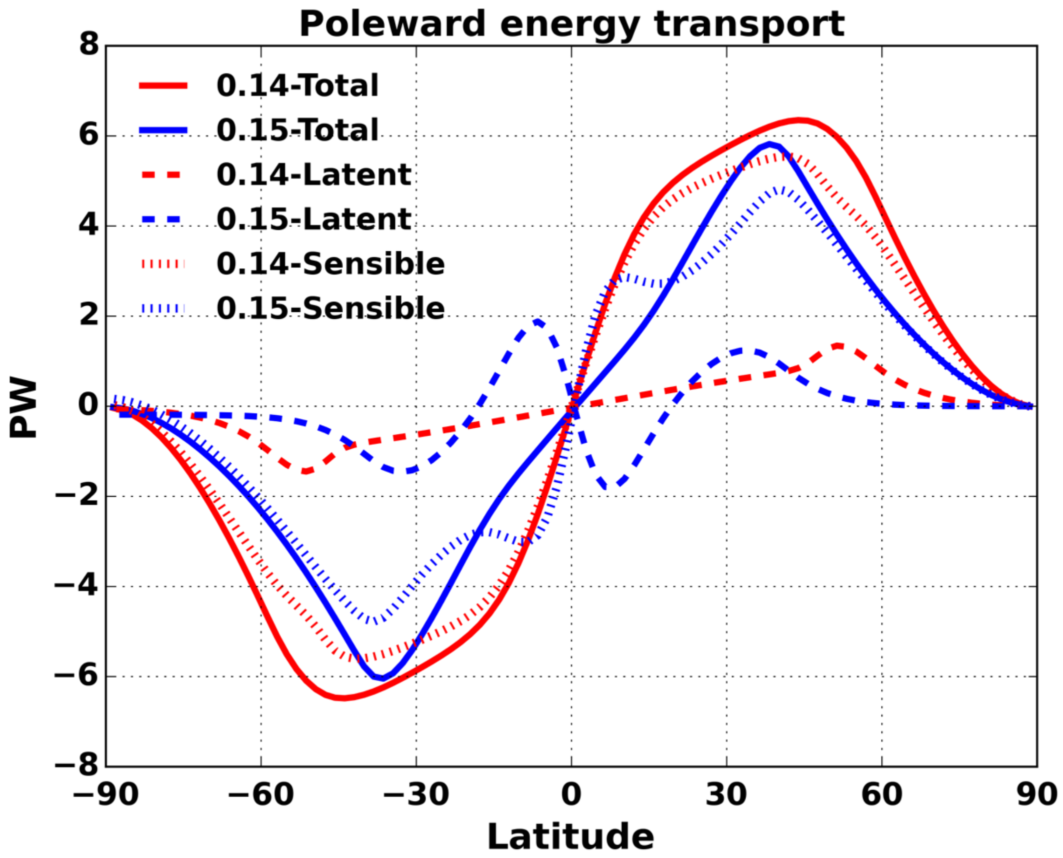


Figure 5: Annual mean behavior of northward transport of total, latent and sensible energy in peta watts (PW) for the two terra-planet states in the simulations Z14 and Z15 averaged over a period of ten years.

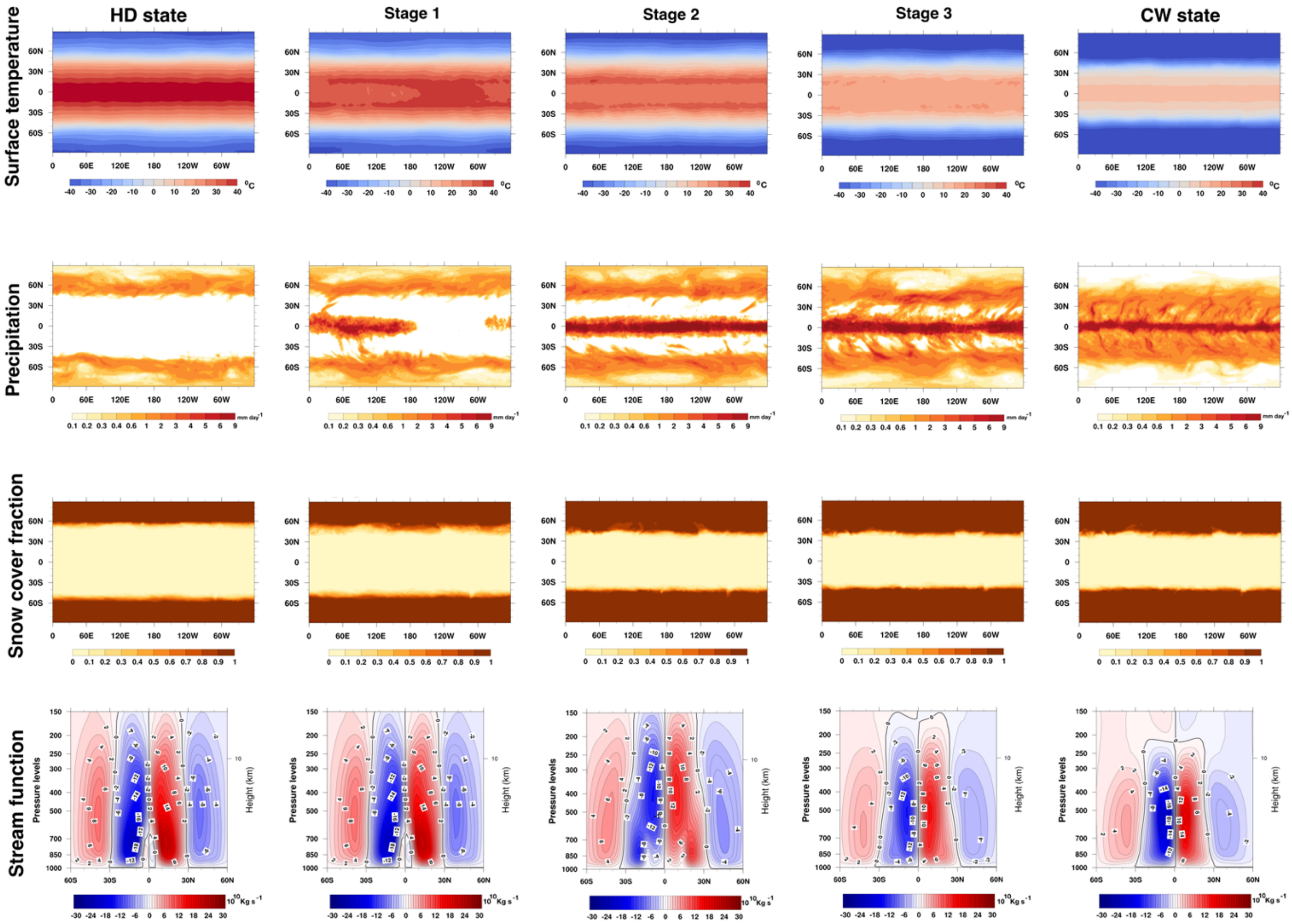


Figure 6: Annual mean surface temperature (first row), precipitation (second row), snow cover fraction (third row) and meridional stream function (fourth row) for different stages of the transition (TRANS simulation) from the HD state to the CW state.

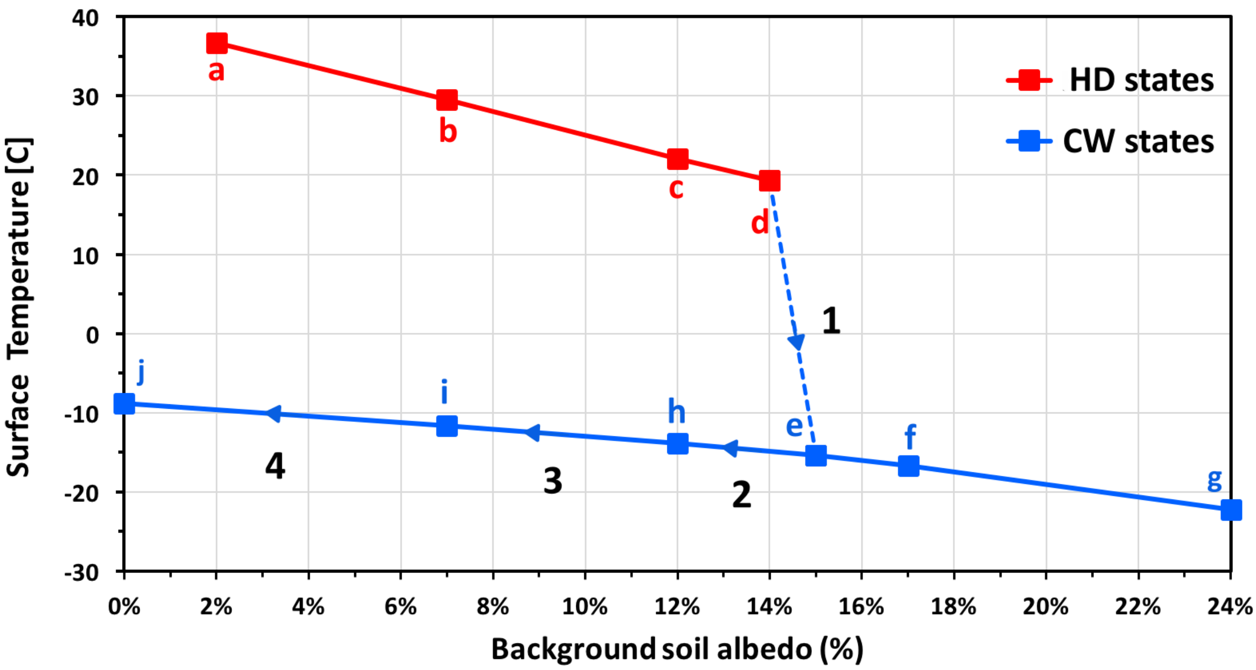


Figure 7: Global mean surface temperature as a function of background soil albedo (α). Simulated HD states are denoted by points a-d and simulated CW states by e-j. Path 1 denotes the spontaneous transition from HD to CW when increasing α and paths 2, 3 and 4 denote the reverse state development upon stepwise lowering of background albedo starting from the threshold value until zero. Obviously, the hysteresis doesn't close for the terra-planet at zero obliquity considered here.

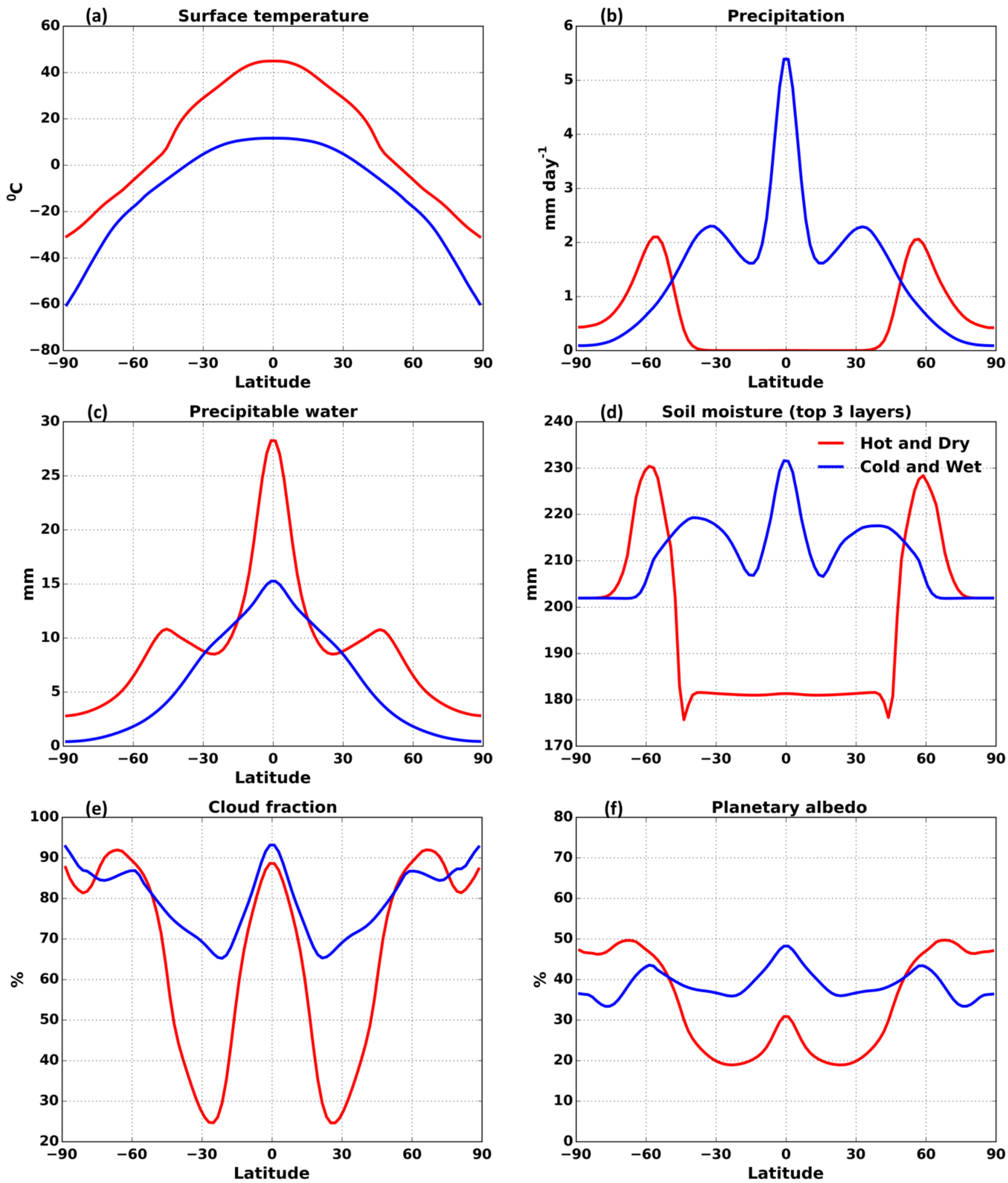


Figure 8: Annual mean meridional profiles as in ~~of (a) surface temperature, (b) precipitation, (c) precipitable water, (d) soil moisture (averaged over the top three layers), (e) cloud fraction and (f) planetary albedo for the two terra-planet states averaged over a period of ten years similar to the~~ Fig. 2 but with dark snow (snow albedo is same as background soil albedo – DS simulation).

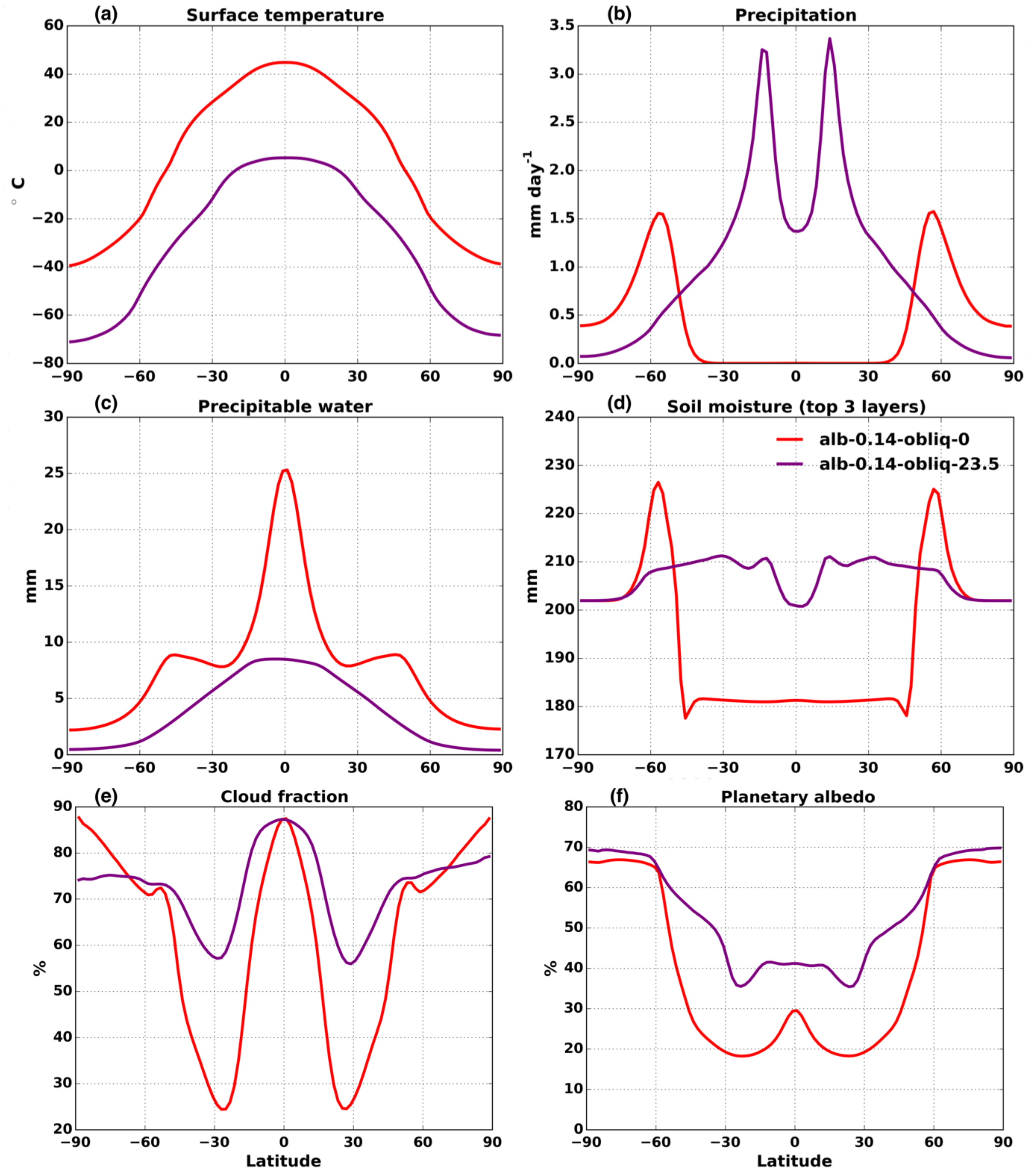


Figure 9: Annual mean meridional profiles ~~of (a) surface temperature, (b) precipitation for the two terra-planet states with the same albedo of 0.14 but obliquities: 0° (red lines – Z14 simulation in Table 1) and 23.5° (blue line – S14 simulation in Table 1) averaged over a period of ten years.~~ as in Fig. 2. The red lines represent the HD state as in Fig. 2 (Z14 simulation in Table 1 with an obliquity of 0°). The purple lines correspond to the simulation with same initial conditions as in the HD state in Fig. 2 but with an obliquity of 23.5° (S14 simulation in Table 1).

Simulations	Background soil albedo	Surface roughness	Heat capacity	Snow albedo	Water reservoir depth
Aqua-planet	0.07	Ocean	Ocean	0.07	50 m slab ocean, no heat transport
Swamp1	0.07	Ocean	Ocean	0.07	Constant ground water table at a depth of 0.3 m
Swamp2	0.07	Land	Land	0.07	Constant ground water table at a depth of 0.3 m
HD	0.07-0.14	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m
CW	0.15-0.24	Land	Land	Dynamic (0.4 -0.8)	Constant ground water table at a depth of 1.2 m

Table A1. Summary of simulations performed to illustrate the procedure followed by which we found bi-stability on our terra-planet.

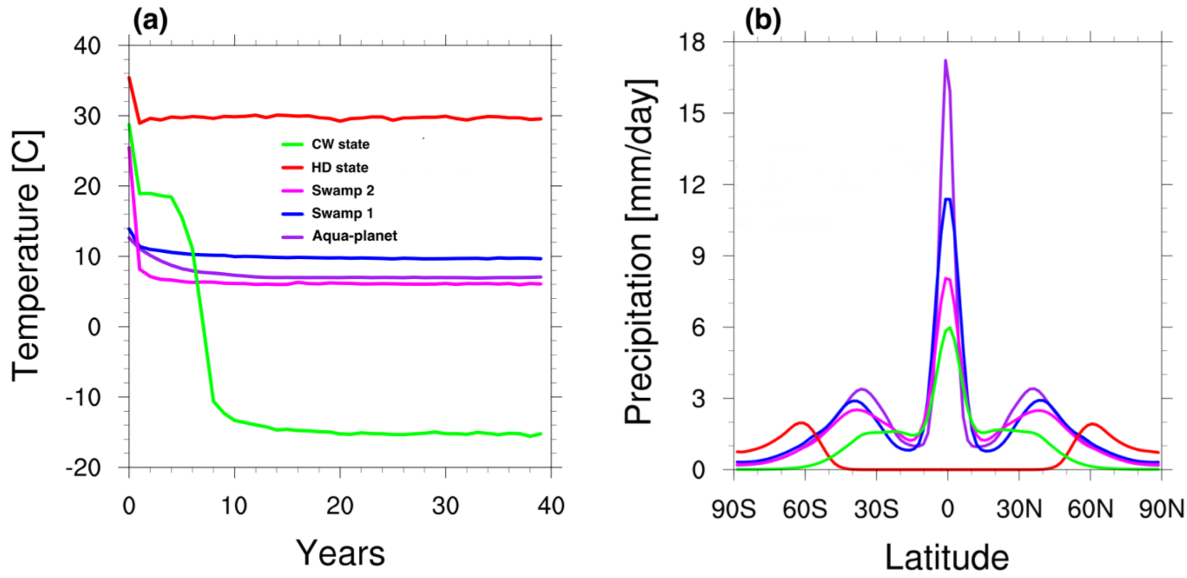


Figure A1: (a) Time series of global mean surface temperature (°C) and (b) annual mean meridional profile of precipitation (mm day^{-1}) for different simulations performed to illustrate the procedure by which we found bi-stability on our terra-planet.

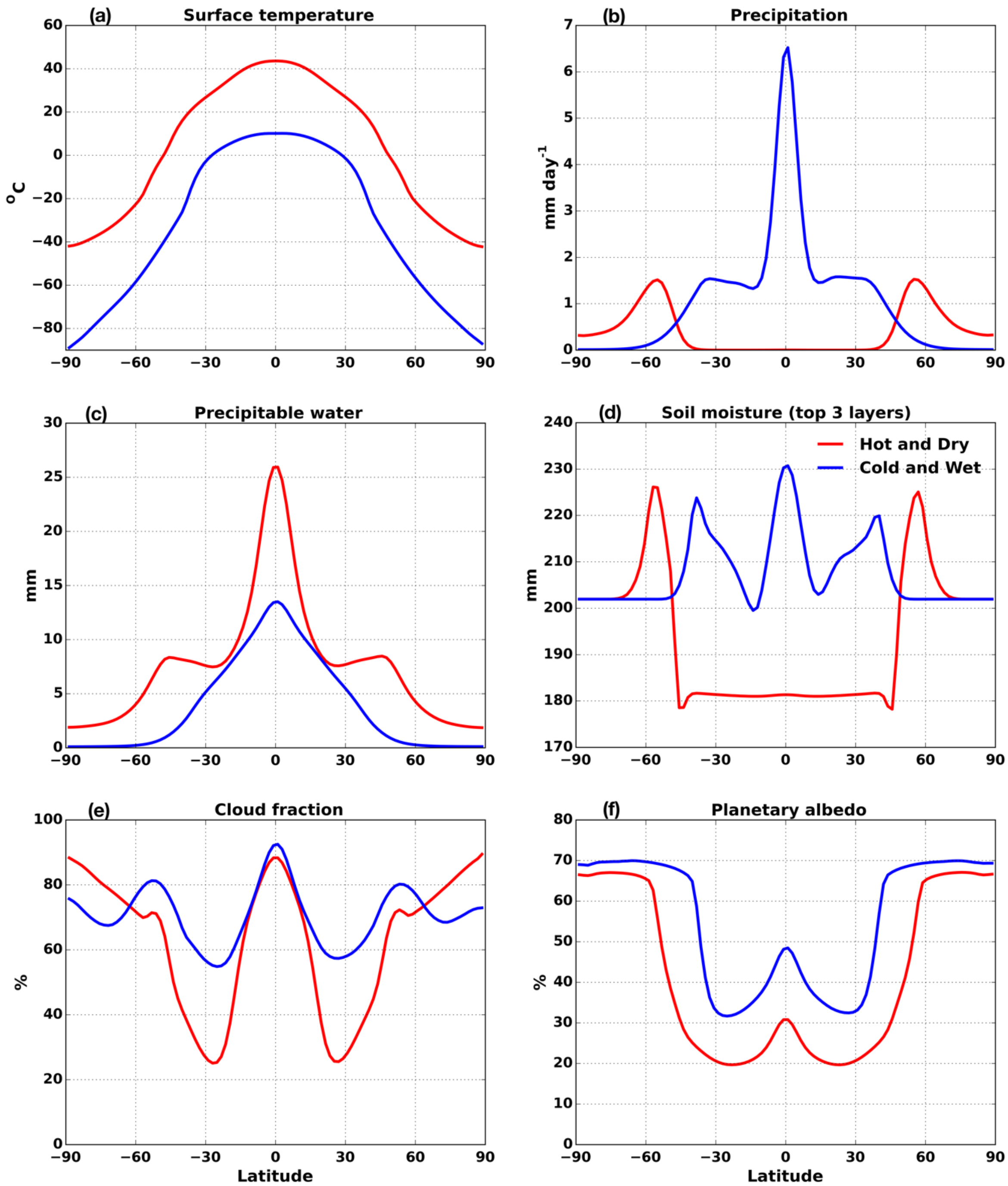


Figure ~~A~~B1: Annual mean meridional profiles ~~of (a) surface temperature, (b) precipitation, (c) precipitable water, (d) soil moisture (averaged over the top three layers), (e) cloud fraction and (f) planetary albedo for the two terra-planet states averaged over a period of ten years similar to the~~ as in Fig. 2 but with Tiedtke convection scheme plotted using T simulations in Table 1